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Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee

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U.S. Department of Transportation
Federal Aviation Administration

Office of Aviation Safety
Washington, D.C. 20591

Final Report
Volume I

June 26, 1978 through
June 26, 1980

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16. Abstract

The Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee and its technical supporting groups spent nearly 13 months from May 1979 through June 1980 examining the factors affecting the ability of the aircraft cabin occupant to survive in the post-crash fire environment and the range of solutions available. Having only a limited amount of time available, the Committee confined its examination to large transport category aircraft, reasoning that recommendations developed could provide the necessary guidance for the FAA to address the broader spectrum of airplane and rotorcraft fire safety improvement. During the course of this assignment, certain topics that were outside the scope of the Committee, yet have some bearing on aircraft fire in general, were identified but not discussed by the Committee. Some of these topics were felt to be worthy of further examination by the FAA or by some other body of advisors constituted for that purpose. These topics are not addressed in this report.

Presentations were made to the SAFER Committee by Committee members, technical supporting groups, the FAA, citizens and private firms. The broadly-constituted body of information developed and presented to the Committee formed the basis for Committee Findings and Recommendations. The Committee focused its recommendations on solutions or interim improvements.

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PREFACE

Fire has always been a safety concern throughout history. In the aviation field, aircraft fires are similarly of concern to the designer, the operator, and of course, to the aircraft occupant. Since the advent of the jet transport aircraft, these larger structures have offered considerably improved occupant protection in the event of a crash. However, aircraft fires, ranging from small easily controlled events to intense post-crash fires resulting from large fuel spills, though rare, continue to account for some loss of life or injury to occupants in aircraft accidents. To examine the possibilities for further reducing the severity or occurrence of aircraft fires and explosions, the FAA established the Special Aviation Fire and Explosion Reduction (SAFER) Advisory Committee. This report is a summation of a year-long study of the problem by the Committee and supporting groups.

The report consists of two volumes: Volume I contains a summary of the Committee's findings and recommendations, along with discussions of the major factors affecting aircraft fire, occupant survivability, and prospects for safety improvements in the context of state-of-the-art understanding. Selected references to current technical literature pertaining to aircraft fires and explosions complete Volume I. Volume II contains SAFER-generated material, consisting of reports of technical support groups, briefings and the summary proceedings of the SAFER meetings.

Events leading to the establishment of the SAFER Advisory Committee began with two FAA public hearings in 1977. The first, in June, considered fire and explosion hazard reduction. The second, in November, dealt with the fireworthiness of compartment interior materials.

As a consequence of the information developed at those hearings, the FAA concluded that the pending rulemaking actions on fuel tank explosion protection flammability, toxicity and smoke production concerning cabin materials were premature and subsequently withdrew in favor of a careful reexamination of the technologies involved in reducing those hazards.

To focus advice from all interested segments of the community at large for this reexamination, the FAA established the SAFER Advisory Committee on June 26, 1978, with an Office of Management & Budget (OMB) approved term of 2 years.* The charter of the committee states that it shall "examine the factors affecting the ability of the aircraft cabin occupant to survive in the post-crash environment and the range of solutions available." Selection and approval of committee members in accordance with the established Federal regulations took approximately 11 months.

The committee met for the first time on May 10-11, 1979, at FAA Headquarters in Washington D.C. In view of the remaining term of about 13 months, the scope of the committee's activities was limited to transport category aircraft and to design aspects of the aircraft relating to fire and explosion reduction.**

*SAFER was established in accordance with Public Law 92-463, Title V, U.S. Code, Appendix 1.
**FAA Agency Order 1110.88, April 6, 1978.

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Furthermore, the committee agreed to concentrate its attention on impact survivable accidents where control of fire and explosions might enhance occupant survival. The committee was charged with a request from the Administrator to report by October 1, 1979, in an interim fashion on what rulemaking actions could be undertaken immediately to improve fire and explosion safety, and also on what additional actions are necessary for FAA to undertake for the improvement of fire safety. The Summary of Proceedings for the SAFER meeting of September 24-28, 1979, in Volume II, contains these interim recommendations.

In addition to the chairman and executive director, the SAFER committee membership consists of 24 representatives spanning the spectrum of international aviation interests. Airlines, manufacturers, universities, public and private sector research establishments, flight and cabin crews, and consumer organization representation is included as shown in the listing at the end of this section.

To provide the detailed information needed by the broadly-constituted SAFER committee, two technical working groups were organized, one on compartment interior materials and the other on post-crash fuel system fire hazard reduction.

These working groups employed additional specialist sub-groups to: examine short-term rulemaking possibilities in materials, material systems, toxicology, materials evaluation and testing, cabin fire safety, and evacuation slide integrity; to review and identify research and development needs; to review the accident statistics data base; to review fuel tank inerting and explosion suppression concepts; to review crash-resistant fuel tank technology; and to examine the potential of antimisting kerosene concepts.

Considering the totality of the committee, its technical support groups, and the additional people who were brought into the process of examining all of the data availabile, approximately 150 of the world's top experts in fire research, operations, accident investigation, materials development, systems design and aircraft fire and occupant safety were involved.

The technical working groups met on June 26 and 27, 1979, at FAA's National Aviation Facilities Experimental Center (NAFEC*) to establish the procedures by which the speciality groups would convene and interact in order to respond to the Administrator's charge to the Committee. Many small meetings of the specialists followed in July, August, and September. The Technical Groups met on September 24-26, 1979, at NASA Ames Research Center to consolidate the sub-group information and prepare their reports to the parent SAFER Committee on September 27-28. Out of this week-long meeting emerged the interim recommendations to the Administrator.

Those recommendations were considered by the FAA in preparation for the meeting in Los Angeles, March 4-6, 1980, where formal responses to those recommendations were presented by the FAA. Positive action plans for all the recommendations were outlined by the FAA. In addition, arrangement of the final report was discussed and plans were made for the final SAFER meeting at the FAA Technical Center. This meeting took place on June 19-20, 1980, where the draft report was discussed. Inputs were used for subsequent editorial review in Washington, D.C. on June 26, 1980.

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A listing of the membership of the SAFER Advisory Committee and the Technical groups on Compartment Interior materials and Post-Crash Fire Hazard Reduction follows:

*NAFEC was renamed FAA Technical Center on June 1, 1980.

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SAFER Advisory Committee Membership

J. H. Enders, Chairman	Aviation Consultant
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SUMMARY

The Special Aviation Fire and Explosion Reduction (SAFER) advisory Committee and its technical supporting groups spent nearly 13 months from May 1979 through June 1980 examining the factors affecting the ability of the aircraft cabin occupant to survive in the post-crash fire environment and the range of solutions available. Having only a limited amount of time available, the Committee confined its examination to large transport category aircraft, reasoning that recommendations arrived at would provide the necessary guidance for FAA to address the broader spectrum of aircraft and rotorcraft fire safety improvement. During the course of this assignment, certain topics that were outside the scope of the Committee, yet had some bearing on aircraft fire in general, were identified but not discussed by the Committee. Some of these topics were felt to be worthy of further examination by the FAA or by some other body of advisors constituted for that purpose. These topics are not addressed in this report.

Presentations were made to the SAFER Committee by Committee members, by the Technical Supporting Groups, by the FAA, and by individual public citizens and private firms. The broadly-constituted body of information developed and presented to the Committee formed the basis for Committee Findings and Recommendations. The Committee focused its recommendations on solutions or interim improvements.

At the FAA Administrator's request the Committee has provided some background discussions of factors involved in aircraft fire and explosion safety assurance that would expand on the findings and recommendations to reflect not only the present understanding of the these factors, but also some view of the outlook for improvements. Individual Committee members who are expert in a given topical area were assisted by the technical support group members in providing the background discussions that follow this summary.

The SAFER Advisory Committee's advice to the FAA is embodied in this final report in the form of consensus findings and recommendations, background discussions, pertinent technical bibliography affecting aircraft fire and explosion safety improvements, and Technical Support Group reports to the Committee.

FINDINGS

On the basis of the information available to it and the subsequent discussion, the SAFER Advisory Committee finds that:

- The overall safety record of U.S. scheduled air carrier aircraft shows a continuing reduction in the fire-involved accident rate since the advent of jet transport service in 1958. The accident and fatality rates per passenger mile, based on available data, show a steady decrease over the past 15 years. (See Part I)

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Over the past 15 years, fatalities due to postcrash fire or its effects in U.S. scheduled air carrier operations average about 32 per year. In addition, occupants have been seriously injured in survivable accidents where postcrash fires occurred. The exact number of those injured and the extent of injuries are not available. (See Part I)

- Ignition of aircraft fuel spilled due to structural breakup during a crash is the primary cause of nearly all aircraft post-crash fires. The major hazard in postcrash aircraft fires is the aircraft fuel supply.

- Though outside the scope of the SAFER Committee, in-flight cabin fires leading to fatalities were found to be rare events. Except for three non-U.S. accidents, all in-flight cabin fires have been controlled by means of design, fire extinguishing equipment and crew training. (See Parts I, II, V and VII)

- The available data base on aircraft fire accidents and incidents is inadequate to determine, with confidence, the critical chain of events in many aircraft fires. (See Part I)

  The role of combustible cabin contents vis-a-vis spilled fuel, in contributing to the hazard of post-crash fires is not adequately defined by presently available accident data or laboratory data to permit a precise judgment of the degree of safety improvement added by substituting improved materials. (See Parts I and III)

  Accident data indicate a general fire safety benefit from materials used in present wide-body jet aircraft compared with those used prior to the FAA's 1972 revision of aircraft interior material flammability standards. The Committee notes that new, improved materials and designs, exceeding these requirements, are often incorporated into aircraft cabin interiors as they become available. (See Part I and III There is a lack of universally accepted test methodology that will reliably predict large scale fire behavior of materials based on small scale tests. (See Part II)

  Current burn and smoke test methods provide the designer with a guideline for selecting materials on a comparative basis. Since these methods do not permit the assessment of the effect of a given material on the overall cabin fire safety level, further study of this area is needed. (See Parts II, III and IV)

- Cabin interior panels and insulation with improved fire resistance are coming into production. This development promises to improve resistance against penetration of an external fire into the cabin. Improved fire resistant windows and cabin wall insulation materials are being evaluated for possible application to the problem of fire penetration resistance. (See Parts II and III)

  Materials that passengers wear or carry aboard an aircraft represent an uncontrolled source of fuel for a post-crash fire, that may add to the cabin interior fire. (See Parts II and III)

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- Near-term improvements in cabin fire safety can only be accomplished by new designs employing currently-available materials. The work on fire-blocking layers for seat cushions is an example. Improvements that depend on new polymers and other break-throughs will of necessity be further in the future. (See Parts II and III)

- Current technology indicates that the FAA C-133 test facility, in conjunction with NASA and industry large scale test facilities is the most reasonable method for evaluating designs and systems effects. Acceleration of the C-133 test schedules at the new FAA Technical Center fire facility will likely satisfy the Committee's interim recommendation concerning these tests. (See Parts II and VI)

  The state of fire modeling capability is a major technical deficiency at present. Existing surface structure fire modeling is not readily applicable to aircraft. Predictive capability of valid fire models would greatly shorten the time now needed to screen and evaluate materials and designs. (See Part III) o The Bunsen burner test now specified in FAR Part 25, Appendix F, is a valid flammability test except for those materials that melt and thereby shrink away when the flame continuous to be applied. (See Part III)

  The FAA, with cooperation from industry, is making good progrers in evaluating improvements to escape slides for fire heat radiation resistance. (See Parts II and III)

- The Ohio State University (OSU) calorimeter testing device provides estimates of flame spread and rate of heat release rates under a realistic radiation flux and, if successfully modified for smoke and toxic gas measurements, offers promise for providing a data base for regulatory actions. (See Part II)

- Since 1959, four accident situations were identified involving fuel tank explosions which are now prevented or substantially delayed by subsequent suitable design changes. (See Parts I and II)

- The concept which has the greatest potential for reducing postcrash fire risk is anti-misting kerosene (AMK). (See Part IV)

- Fuel tank inerting would provide very limited benefits in a post-crash accident where only minor tank rupture occurs. If a tank is not ruptured, the likelihood of fire is reduced. (See Parts II and V)

- Translation of military aircraft fuel tank fire quenching foams and foils to large, complex, civil transport tanks presents design/ redesign weight and maintenance difficulties and adds excessive operational penalties.

- Little is known concerning the performance of military foams and foil under external fire conditions or post crash fire situations accompanied by significant wing break-up. (See Part V)

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- The complexity of presently available vent fire suppression systems, when extended to complete fuel system protection, would introduce excessive operating penalties. (See Part V and VIII)

- It is feasible to install crash-resistant fuel cells in the fuselage. It may be feasible to incorporate some degree of crash resistance in critical wing fuel tank locations. It is not feasible, in most conventional transport aircraft, to install all wing fuel in crash resistent fuel cells. Current FAR's do not preclude incorporation of such design features. (See Part V)

- Toxicity test standards do not exist for aircraft fire situations. Further, there is no agreement among specialists on the approximate magnitude (statistical) of the toxic contribution from burning interior materials relative to the contribution from burning turbine fuel or other fire related hazards. (See Part IV)

- There is incomplete data on the hazards from exposures of humans to toxic gas mixtures likely to be emitted from aircraft cabin materials or fuel during a fire. (See Part IV)

- Irritants (gases and smoke) may have a real but unquantified effect on slowing egress from an aircraft. (See Part IV)

- While certain well done toxicity research projects have been carried out, there has been no substantial effort devoted to understanding the overall toxic threat environment in aircraft fire situations. (See Part IV)

- Reduction of the potential toxic threat from thermal decomposition products by controlled selection of interior materials on the basis of relative performance in a small-scale toxicity test with experimental animals cannot be recommended at this time. (See Part IV)

  For the purpose of material selection, assessment of relative toxicity, solely from results of chemical analysis for selected components of thermal decomposition products cannot be recommended at this time. (See Part IV)

- Consistent with overall aviation budgetary needs, aircraft fire research has, with the exception of toxic hazards assessment, been reasonably well funded since the early- to mid-1970's. Improvements expected within the next year or so are products of research begun in that period. (See Part VI)

  The development and use of fire scenarios that depict real fire situations would focus engineering and regulatory improvements on aircraft fire and explosion reduction, and toward improvements in evacuation procedures. (See Part II, V, and VIII)

  There is good coordination of aircraft fire R&D between the U.S. and European research organizations, resulting in more rapid progress than there would have been without this exchange. (See Part VI)

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On the basis of these findings and the discussions that led to them, the Special Aviation Fire and Explosion Reduction Advisory Committee recommends the following actions to the FAA. The SAFER Committee urges the FAA to implement these recommendations as quickly as possible. A number of proposals involve research and development that will take several years to complete and, unless the R&D is begun soon, the target dates for completion will be pushed even further into the future. Such delay could retard introduction of the safety benefits derived from prompt action on these recommendations.

RECOMMENDATIONS
(In order of Priority)

POSTCRASH FIRE HAZARDS

- Expedite the investigation and validation of antimisting kerosene (AMK) as proposed in the FAA, AMK Engineering and Development with the NASA and the United Kingdom agencies. The proposed AMK/E&D program plan presented to the committee in March 1980 incorporates the SAFER Committee interim recommendations on this topic, made in September 1979. The Committee supports the FAA planned target date of 1984 for the establishment of the data base for initiating rulemaking procedures.

  NOTE: The Committee is of the view that, if successful, the AMK technology could provide the single most significant safety improvement to reduce the post-crash fire hazard.

- Amend FAR Part 25 to require fuel tank vent protection during ground fires by adding a new paragraph 25.975(a)(7) to read: "Each vent to atmosphere must be designed to minimize the possibility of external ground fires being propagated through the vent line to the tank vapor space, providing that the tank and vent structure remain intact." The Committee recommends that this action to amend FAR 25 begin immediately and be completed within 12 months.

- Amend FAR Part 25 to require design practices that maximize the probability of engine fuel supply shut-off in potential fire situations.

- Investigate the effect on fire safety of reduced flash point of kerosene fuels. These should be investigated concurrently with the AMK research.

  NOTE: Efforts must continue in this area prior to the use of AMK or in the event that AMK additives are not practical.

- The FAA should immediately request the NTSB to consider implementing the proposals by the Coordinating Research Council for improved accident reporting relevant to postcrash fuel fires. The Committee notes that the Coordinating Research Council made this recommendation in 1975 in their report No. 482. (See Volume II). The information obtained would greatly assist designers in reducing fire risk.

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- Continue and expedite FAA/NASA research to establish realistic airplane crash scenarios with increased emphasis on postcrash fuel system failure modes and effects on cabin fire safety.

- From the crash scenarios, develop fuel system design criteria for transport category aircraft in order to minimize postcrash fuel fires.

CABIN INTERIOR MATERIAL

- The SAFER Advisory Committee, in developing the following cabin interior materials recommendations, took cognizance of the proposed FAA Cabin Fire Safety research plans in terms of technical objectives, funding requirements, and milestones. The plan should develop the technical data base that would support FAA's decision on eventual rulemaking, targeted for 1984, which will lead to improved human survivability in post crash fires. Several of the following recommendations are based on intermediate milestones of the FAA Cabin Fire Safety Research Plan.

- Establish the contribution of cabin interior materials to the postcrash fire hazard. The role of current materials, under fire conditions, should be established by mid-1981.

- Develop for aircraft seats, fire blocking layers (e.g., fire barriers) for polyurethane foam cushioning material, in order to retard fire spread. The initial development should be completed by early 1981.

- Expedite the development of the Ohio State University (OSU) chamber and evaluate its use. If successful, this would provide a standardized test for materials which would account for flammability, toxicity, and smoke. The Committee expects that this development could be completed by late 1982, at which time its use should be considered for incorporation in FAA's fire airworthiness rules.

- Accelerate toxicity research efforts to identify and understand the biological, chemical, and physical factors that must be integrated into comprehensive fire risk assessments for materials in specific end-use configuration. Because of the state of technology, there is no near-term solution to this problem. The Committee recommends that, by early 1981, FAA develop a detailed toxicity research program plan that will provide a basis for eventual regulatory action.

- Amend the FAR Part 25, Appendix F, Flammability Test Method for Materials, after the American Society for Testing and Materials (ASTM) has modified test (Bunsen Burner Test ASTM-F7 Method F-501) to account for the melt and drip-away behavior of certain materials. The FAA should urge the ASTM to expedite this test procedure modification and should complete the incorporation of the Amendment within one year thereafter.

- Define postcrash aircraft fire scenarios and establish their applicability to fire modeling, research, and design. The Committee recommends that this be accomplished by mid-1981.

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- Continue to expedite and coordinate full-scale fire test plans.

  Note: The Committee supports recent FAA actions to expedite its C-133 full scale fire test program as part of the overall Cabin Fire Safety Plan. The Committee supports the FAA's planned target date of late 1982 for completion of all major aspects of the C-133 program including correlation of small-scale with large-scale tests.

- Coordinate and accelerate development of analytical postcrash aircraft fire modeling approach as a means of focusing on those physical fire test and evaluation methods most likely to yield practical results in the earliest possible time. Both small and full-scale test results are required for fire modeling validation.

- Based upon the FAA preliminary evaluation of the test procedures and present materials for evacuation slides completed in May 1980, the Committee recommends that FAA support continued research and establish radiant heat resistance standards and criteria for inflatable evacuation devices at the earliest possible date.

- Expedite the development of improved fire resistant cabin windows to protect the cabin occupants from external fuel fires. Adaptation of such improved window materials will require further service environment evaluation prior to aircraft useage.

- Promote open forums, documents and presentations to make the complex subject of toxicology more understandable to regulatory bodies, flight crews and the public.

- Encourage on a continuing basis the development of a cabin interior material data bank to serve as a central information source for materials characteristics for aircraft designs.

- Support the continued development of advanced materials to accomplish long-term improvements in aircraft cabin fire safety, including low smoking fire resistant seat foams.

OTHER AREAS OF CONCERN

The Committee recognized that there were many potentially worthwhile concepts for improving aircraft fire safety that it simply did not have time to fully address or that were outside the scope of its review. Recommendations relating to such concepts are:

- That FAA evaluate the use of self-contained smoke masks, gloves, clothing, or other personal protection equipment for crewmembers in order that they can better complete emergency evacuation of occupants under the postcrash condition. Such protective equipment could be helpful in assisting the evacuation of infirm or handicapped persons.

- The Committee strongly recommends that NTSB and FAA jointly improve and standardize postcrash accident investigations with added emphasis on identifying the role of design features and materials that affect the

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development and spread of postcrash fires. Features that contribute to fire safety as well as those that contribute to fire hazards should be identified. Likewise the precise cause of death and/or injuries in postcrash fire accidents should be determined where practicable.

Recognizing that SAFER Committee's efforts are only a beginning in focusing the technical and regulatory attention necessary for rational aircraft fire safety improvement, the Committee further recommends that FAA move rapidly to establish a standing technical advisory committee structure in the manner of the highly-successful NASA Research and Technology Advisory Committees and the Air Force Scientific Advisory Board. Such a body would provide regular and frequent specialist advice, over the long-term, to the FAA aircraft fire and explosion research program. In particular, the fire safety issues outside the scope of SAFER, or those needing more detailed examination than SAFER could offer, could be addressed for all aircraft types. This recommendation is consistent with a recommendation expressed by the National Research Council's Committee on FAA Airworthiness Certification Procedures on June 26, 1980.

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I

AIRCRAFT POST-CRASH FIRE PROBLEM DEFINITION

Introduction:

It was determined at the first SAFER meeting:

1. That the Committee would confine itself to transport category airplanes.

2. That, with respect to such airplanes, the Committee would confine itself primarily to the post-crash fire issues discussed at the June 1977 public hearing on fire and explosion hazard reduction and at the November 1977 public hearing on compartment interior materials.

3. That, when considering compartment interior materials issues, the Committee would also consider the matter of carry-on materials (i.e., baggage, clothes, periodicals, cabin supplies, etc.) and the fuel fire heat radiation resistance of emergency evacuation slides.

4. That other issues would be considered only if they are comparably significant and directly related to the post-crash situations.
The first two of those in particular are important in defining the scope of the Committee's activities and are extremely important in defining the magnitude of the aircraft fire problem.

There have been numerous surveys of airplane accidents, both in the US and world-wide (References 1 to 7), which attempt to put the airplane fire problem in perspective. All of these suffer from a lack of adequate information in one form or another and are thus subject to conjecture and interpretation. variations in the scope and definitions used in compiling the data base lead to further numerical differences, but there is general agreement among the various sources as to the magnitude of the aircraft post crash fire problem.

In view of the fact that the basic purpose of the SAFER activity is to support the development of fire safety regulatory requirements applicable directly to US airplanes and only indirectly to non-US airplanes, it was expedient to limit the data in this report to the experience of US air carriers. Detailed data can be obtained directly from reports issued by the US National Transportation Safety Board (NTSB) (Ref. 8) which is reponsible for accident investigations of US operators. It is believed this experience is representative of world-wide scheduled air carrier operations.

The vast majority of current US air carrier operations are conducted in turbine powered transport category airplanes and any new regulatory action which may evolve would no doubt be directed first towards that class of airplane. It is, therefore, appropriate to confine the scope of the investigations to that type of airplane.

Two accidents to US turbine powered airplanes played important roles in initiating the activity SAFER is concerned with. The first of these was the Pan American 707 at Elkton, Maryland in 1963. This was an inflight fuel tank

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explosion and, although outside of the scope of SAFER as presently constituted, it led to the establishment of the FAA Advisory Committee on Fuel System Fire Safety and the promulgation of FAA Notice 74-16 on Transport Category Turbine Powered Airplanes Fuel Systems Explosion Prevention. The second accident which triggered interest not only in fuel system safety but in the fire safety of cabin interior materials as well, was the United 727 at Salt Lake City, Utah in 1965. As the result of each of these accidents, regulatory action was taken by FAA to minimize the potential for recurrence. These changes involved lightning protection, fuel system fire protection and rules on cabin interior materials. These regulatory actions and further proposed rulemaking led to the establishment of SAFER to provide a forum for a comprehensive review of transport aircraft fire safety regulatory requirements.

Based on the preceding, it is considered appropriate that any attempt to determine the scope of the airplane post-crash fire problem should not delve into "ancient history" but consider only more recent times. The data which follow are thus confined to post-crash fires involving:

1. Transport category turbine powered airplanes in US air carrier service.

2. The period 1965-1979 inclusive.

3. Accidents in which fatalities were attributed to post-crash fires.

The Magnitude of the Aircraft Fire Problem

As can be seen in Figure 1, the safety record of the scheduled airlines is excellent when compared to other transport modes. 1979 data are not available for the other transportation modes, however, for the US air carriers there were a total of six fatal accidents in 1979 (including one helicopter accident) of which three involved turbine powered transport category airplanes.
The airlines flew a total of 280 billion passenger miles and the fatality rate was 0.115 per hundred million passenger miles.

Figure 2 shows the five year average fatality rate per 100 million passenger miles for US certified route air carriers in scheduled domestic and international passenger service for the period 1959 through 1979. In spite of recent dramatic fatal accidents, the trend is still downward.

Since we are concerned not only with scheduled passenger service but all operations of US carriers turbine powered airplanes, available NTSB statistical data covering such operations were reviewed. This indicates in the period 1965-1979 inclusive there were a total of 605 accidents (as classified by NTSB) involving turbine powered transport category airplanes. Of these 605, there were 96 fatal accidents or 16 percent. According to the NTSB report shown as Reference 5, the following post-crash fire accidents accounted for all of the fatalities from fire in US air carrier operations of turbine powered airplanes for the period 1965-1974.

1.	November 8, 1965	American 727, Cincinnati, Ohio
2.	November 11, 1965	United 727, Salt Lake City, Utah
3.	November 20, 1970	Capital DC-8, Anchorage, Alaska

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Safety

Comparative Transport Safety Record

Passenger Fatalities per 100 Million Passenger Miles	1978	1977	1968
U.S. Scheduled Airlines			
Domistic Interstate			
Fatalities	13	64	258
Rate	0.007	0.038	0.30
International and Territorial			
Fatalities	0	0*	47
Rate	0	0	0.18
Total			
Fatalities	13	64*	305
Rate	0.006	0.031	0.18
Motor Buses			
Fatalities	2	6	31
Rate	.012	0.040	0.16
Railroads			
Fatalities	13	4	13
Rate	.017	.005	0.10
Autos			
Fatalities	29,000**	28,685	36,500
Rate	1.6**	1.4	2.3

*Does not include 321 passenger fatalities in nonscheduled international service.
**Estimated

FIGURE 1

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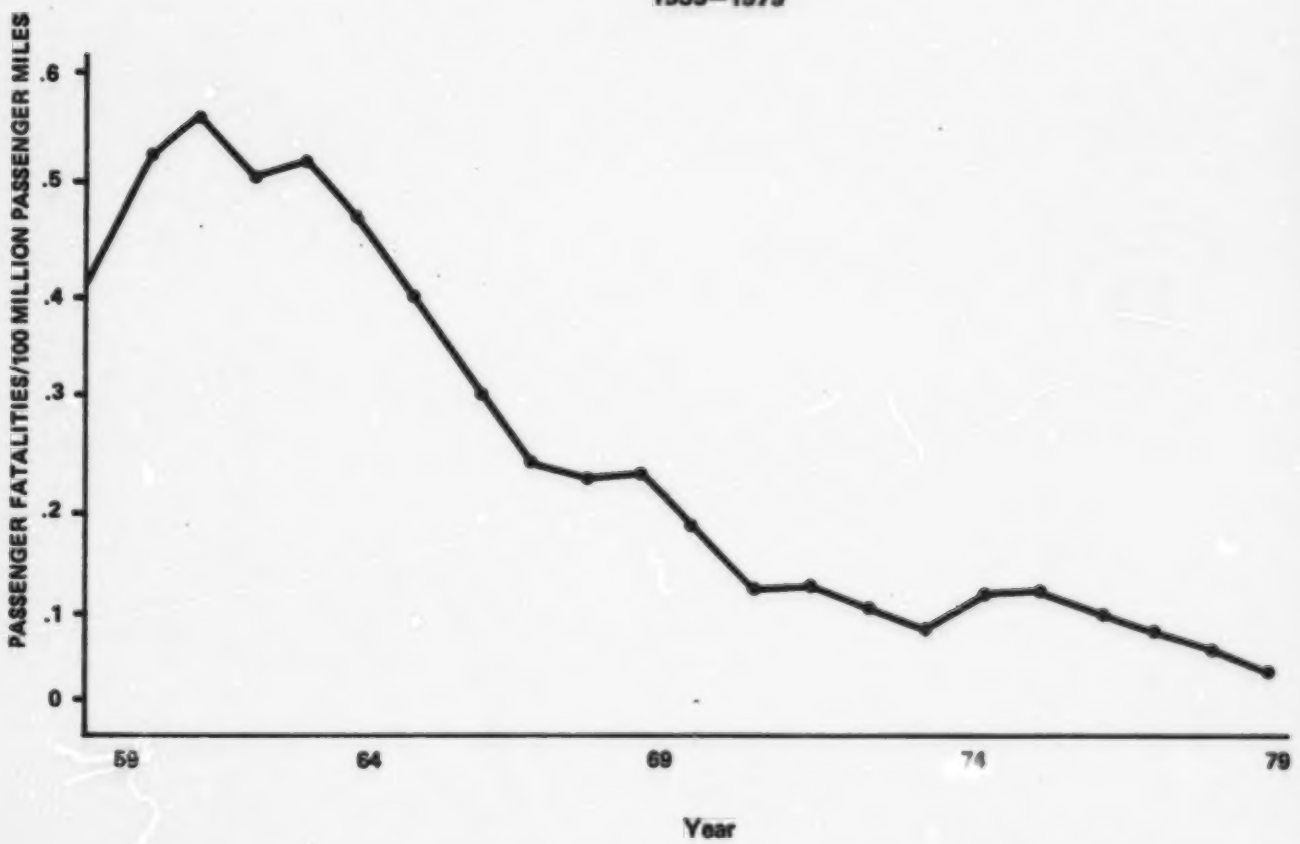
5 Year Average Fatality Rate/100 Million Passenger Miles
U.S. Certified Route
Air Carriers - Scheduled
Domestic and International
Passenger Service
1959–1979



1/ Accidents such as Tenerife in 1977 and San Diego in 1978 did not involve scheduled service by U.S. certificated route carriers and are not included in these rates. However, the inclusion of such statistics would not significantly alter the downward trend.

FIGURE 2

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4.	December 28, 1970	Trans Caribbean 727, St. Thomas, Virgin Island
5.	June 7, 1971	Allegheny CV-580, New Haven, Connecticut
6.	May 30, 1972	Delta DC-9, Fort Worth, Texas
7.	December 8, 1972	United 737, Chicago, Illinois
8.	December 20, 1972	North Central DC-9, Chicago, Illinois
9.	January 3, 1974	Pan American 707, Pago Pago
10.	September 11, 1974	Eastern DC-9, Charlotte, North Carolina

A review of individual NTSB fatal accident reports for the years 1975 through 1979 indicates that fatalities due to fire occurred in the following post-crash fire accidents:

11.	April 2, 1976	American 727, St. Thomas, Virgin Islands
12.	March 27, 1977	Pan American 747, Teneriffe, Canary Islands
13.	April 4, 1977	Southern DC-9, New Hope, Georgia
14.	March 1, 1978	Continental DC-10, Los Angeles, California
15.	October 31, 1979	Western DC-10, Mexico City, Mexico

There was a fire involved in the Western DC-10 at Mexico City, however, firm data on whether any fatalities can be attributed to fire is unavailable at this time. It is surmised there were fatalities attributable to fire.

From the above, it can be seen that fatalities were attributed to fire in 15 of 96 fatal accidents or about 16 percent. In no case was fire the cause of the accident but rather the result. With the exception of accident number 15 above, for which final data are not yet available, NTSB data shows approximately 1,527 persons were on board of which approximately 831 were fatally injured, of these approximately 480 died as a result of the postcrash fires.

Examination of the NTSB data shows that during this same period there were several post-crash fire accidents to U.S. turbine powered transport category airplanes which did not result in fatalities attributed to fire. Time did not permit the determination of the reasons why no fatalities were attributed to fire in these accidents. Such a study would be useful in defining the effectiveness of existing fire safety requirements. While year-to-year variations occur, the average rate of approximately 32 fire deaths per year has been fairly constant despite the great increase in air travel during this period. This figure may be compared with the approximately 8,000 fire deaths which occur in the United States each year. (Exact comparisons cannot be made owing to varying conditions).

It is of interest to note that during this period (1965-1979) the US air carriers made over 73 million departures and carried about 3 billion passengers. The vast majority of these operations involved turbine powered airplanes. A review of background data for the period 1955-1964 in Reference 5 indicates there were two post-crash fire accidents to US air carrier turbine powered transport airplanes in that period where fatalities were attributed to fire. Thus, in about 22 years of operation of turbine powered transport category airplanes, there have been approximately 17 post-crash fire accidents where fatalities have been attributed to fire.

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While the emphasis in this discussion has been on fatalities, in part because the data on such occurrences are more precise, it is recognized that post-crash fires also frequently cause serious injury to survivors. We believe steps taken to reduce fatalities will also be effective in reducing injuries.

Nature of Transport Aircraft Post-Crash Fire Accidents

In all accidents listed, the initial fire was a fuel fed fire. Wing separation accompanied by massive fuel spillage occurred in about half the accidents. Fuselage fuel tank or fuel line rupture may contribute to fuel spillage in cases of severe fuselage breakage on impact. Fuel tank explosions occur less frequently but are particularly dangerous because they may terminate evacuation, fire fighting and rescue operations. Moderate fuel spills due to tank or fuel line damage are a less serious threat. It is of interest to note that the United DC-8 accident at Portland, December 28, 1978, also involved severe airplane break-up but the cause of the accident was total fuel exhaustion and there was no accompanying fire.

The role of cabin interior materials in causing fatalities in a survivable crash fire is difficult to assess. The external fuel fire may penetrate the cabin through an impact created opening, through a door opened for evacuation, or a hot fire may burn through the relatively thin intact fuselage wall. Once the fire has penetrated into the cabin interior heat, smoke and toxic combustion products from ignited interior materials will mix with those from the external fire, leading to the rapid development of untenable conditions.

The rate at which the fire grows will depend on the quantity, disposition and flammability properties of the combustible cabin contents, as well as the ventilation of the fire. Tests have shown that a fire within a typical aircraft cabin can develop untenable conditions in a time comparable to the normal evacuation time.

Combustible materials within the aircraft cabin will consist of cabin interior finishes and furnishings, passenger clothing, passenger carry-on items and cabin supplies (Ref. 9, See Volume II). Furnishings and finishes constitute the largest class of combustibles. Since they meet the requirements of FAR 25.853 they may be slow to ignite but can burn vigorously when exposed to a sizeable fire. Passenger clothing is present in smaller quantities but is more readily ignited. Carry-on items will usually be of low flammability and will be stored under seats and in protected compartments where they are less vulnerable. Cabin supplies are a minor part of the fuel load and are stored in protected compartments. All combustibles may be displaced on impact and thus become more vulnerable to fire.

Adequacy of Aircraft Accident Data

A sound plan of attack on any safety problem must start with a careful analysis of the accident data in order to pinpoint the true causes of accidents and identify effective remedies. Otherwise, we may devote large amounts of limited resources to solving the wrong problem.

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Aircraft accidents are among the most thoroughly and carefully investigated of all public events. Yet, available aircraft data cannot provide a guide, at this time, to a comprehensive regulatory solution to the aircraft fire problem. A major effort is made to determine the cause of the crash. This is well done and has made an invaluable contribution to the reduction in the frequency of crashes and the number of casualties. SAFER, however, proceeds on the assumption that despite these efforts some crashes will occur. We are concerned with steps that can be taken to reduce the number of casualties in these cases.

Much less effort is given to investigating the course of events following the crash than to the events preceding the crash. This may be due to the belief that the cause of the crash is the cause of the casualties and that subsequent events are unimportant. It is probably also an indication that the investigators are not trained in the investigation of fires. The fire may destroy much of the evidence, making it difficult, even for the expert, to determine the course of events.

As a first step, it is necessary to distinguish between casualties due to impact and those who might have survived if they had not subsequently been killed by fire. This is frequently a matter of subjective judgment based on autopsy data. The investigator is frequently dependent on local medical personnel who are often inexperienced at making such judgments. As a result, we have only rough estimates of the number of fatalities due to fire and of the potential lives that could be saved through improved fire safety regulations.

The time sequence of events is critical to an understanding of the course of a fatal fire. We are concerned with the relative rates of the growth of the fire and the development of untenable conditions and with the rate of evacuation, perhaps aided by firefighting and rescue operations. Such information is difficult to obtain, but it is essential if we are to answer such questions as: what would be the value of more fire resistant seating materials; what would be the value of added insulation in the cabin wall; what would be the value of intumescent coatings?

The exact cause of fire deaths is difficult to determine in civilian fires (Ref. 10) and even more difficult to determine in aircraft fires. The relative importance of high temperatures, smoke obscuration and toxic gas inhalation is unknown. Without information on such questions available, it is not possible to estimate the effectiveness of proposed rules on the flammability, smoke producing potential or toxicity of combustion products of cabin interior materials.

Cost Effectiveness

Economic analyses and cost-benefit studies are required in one form or another by the airframe/airtransport industries and the FAA in evaluating safety as well as other technical improvements. The fact that the next generation transport aircraft will have improved fire resistant materials demonstrates that airframe manufacturers include the safety element in the overall materials selection process. Cost and benefit studies will be required by the FAA to justify improvements to the certification standards whether they be applicable to future designs or newly manufactured or existing aircraft. However, such studies are

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of limited quantitative accuracy and require the extensive employment of subjective judgement. It is important to recognize the current enviable airline safety record and the resultant relatively small number of fatalities. Any safety improvement will be small and incremental but they will save human lives. The resulting economic analyses in themselves may not fully rationalize a "blanket" requirement for safety improvement but may lead to decisions on parts of the solution and identify justified safety improvements. In conducting these analyses, it must be recognized that government and industry resources available for safety are finite and must be very carefully allocated to achieve the greatest benefits.

Aircraft Fire Problem Definition

The preceding is not an attempt to minimize the airplane fire problem but only to put it into perspective. The fact that post-crash fires have occurred is inescapable. The fact that fatalities due to fire occur relatively infrequently in the overall accident record is also inescapable. We do not believe this is just happenstance but is attributable to the combined efforts of people in government and industry who, working together, have achieved the remarkable safety record of the US air carriers. In considering the total accident history, it is evident that the primary effort should be expended in accident prevention - that is where the real payoff is in terms of safety and human life. In spite of dedicated efforts, however, it is evident that accidents will continue to occur and there will be post-crash fires. Thus efforts to improve the public's chances of surviving a crash and post-crash fire cannot be ignored and must continue.

Now that the magnitude of the problem has been defined, we believe it appropriate to define the problem in its simplest terms. Recognizing that post-crash fires will occur, we believe the problem before the SAFER Committee is:

To determine what improvements can be made in fuel systems and in materials in aircraft cabins which are technologically achievable and economically reasonable and will result in significant improvement in post-crash fire safety.

To make this determination, SAFER found it necessary to explore many avenues which are discussed in following sections of this report.

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II

GENERAL CONSIDERATIONS OF AIRCRAFT FIRE AND EXPLOSION HAZARDS

A commercial jet transport carries large quantities of jet fuel and its cabin is lined and furnished with polymeric materials. Passengers and crew members occupy a confined environment where rapid movement and egress can be difficult. Although the overall safety record is excellent compared to other modes of transportation, the potential dangers arising from aircraft fire are great as evidenced by the continuing, although very infrequent, occurrence of fire accidents. The primary concern of the SAFER Committee is directed toward minimizing the dangers associated with burning fuel, burning cabin materials and fuel tank explosions.

Design Constraints

The primary guidelines confronting the aircraft designer, aside from function are safety, economics, serviceability and aesthetics.

Cabin materials are selected from safety considerations based primarily on regulatory flammability requirements (FAR 25.853) and low-smoking tendency (NFPA 258) at the discretion of the airframe manufacturer. In recent years, flammability performance, as indicated by large-scale tests or small-scale flammability tests (e.g., ASTM E-162, Ohio State University test chamber) has had a bearing on material selection. However, progress in the development and selection of improved materials is handicapped by the lack of test methodologies proven to relate to cabin fire hazards, especially in the area of toxicity.

Cabin materials are either selected or furnished by the airframe manufacturers or airlines. The former select and fabricate the lining materials used in components such as sidewalls, stowage bins, ceilings, partitions and structural flooring, while the latter select and replace seating, floor covers, and passenger sevice items. Generally, the state-of-the-art lining materials (panels) used by the major airframe manufacturers are similar in design to one another. The panels are complex composites consisting of a honeycomb core, fiberglass sheet facings, and a thin plastic covering. Replacement of any component because of potential fire performance improvement should be compatible with existing processing equipment and weight allowances if the replacement is to be cost effective. Moreover, the differential in raw material cost between the new and replaced material must be reasonable. Function, appearance, and serviceability of a new panel design cannot be degraded. For these reasons, it is difficult to economically alter current panel designs. These difficulties are not as pronounced for seating and floor coverings. Moreover, seating and floor covering materials are replaced more frequently (6-12 months) because of service wear than the paneling (5-10 years) and thus offer greater opportunity for material changes. There have been cases in the past where material changes based on fire performance considerations have caused service problems. For example, fabric of an inherently fire resistant and low-smoking fiber for seat covers and carpets was evaluated in the early wide body jets but exhibited pilling and poor dye retention after service usage. Potential problems of this

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nature have discouraged the airframe manufacturers and airlines from undertaking material changes because of the questionable nature of the resultant fire safety benefits.

Unlike interior materials, safety fuel and fuel tank explosion protection devices have a direct bearing on the safe operation of an airplane. Ideally, safety fuels must be absolutely compatible with existing fuel storage, fuel transfer and propulsion systems. Similarly, fuel tank protection devices cannot be allowed to alter the fuel tank capacity, impose significant weight penalties, or introduce maintenance and inspection problems.

Fire Scenarios - The issue of aircraft fire safety must be analyzed in the context of survivable fire situations. By definition, a survivable accident is an accidental occurrence in which injuries received by passengers or crewmembers, not attributable to the effects of fire, are such that survival of all or most of those persons is probable. There are three types of survivable fire situations: the ramp fire, the in-flight fire, and the postcrash fire. Ramp fires have usually involved empty aircraft with no loss of life, and are not of direct interest to the SAFER Committee, since losses have been entirely economic. Although there are many incidents of in-flight fires, except for two or three cases they have been controlled so that few fatalities have occurred. The overwhelming majority of aircraft fire fatalities occur as the result of postcrash fires.

In-Flight Fires. This aspect is not part of SAFER's chartered scope, but is treated briefly because it does bear on the basic subject of fire sfety. Aircraft service records and engineering test data substantiate that current aircraft interior materials are adequately resisting the vast majority of in-flight fires to which they are exposed. Thus the current airworthiness rules are believed adequate. Supportive evidence of this is derived in the following typical items treated in these rules.

1. Flame arrestors or fire suppression systems in the wing tip surge tanks provide protection against fuel tank explosions caused by lightning strikes.

2. Accessibility to cargo compartments by crew members has virtually eliminated accidental fires as a serious hazard in such compartments.

3. For inaccessible compartment areas, the fire is successfully controlled by shutting off the normal ventilating air flow and by fire detection and extinguishment systems.

4. Some 92 minor galley fires from 1959 - 1973 have been promptly extinguished with hand-held extinguishers. (Ref. 11.)

5. Although less frequent, there have been a number of fires believed caused by cigarette ignitions which have also been promptly extinguished. However, there was one instnce of an inflight fire, believed caused by the discarding of a cigarette into a lavatory waste paper towel disposal compartment, which resulted in 124 fatalities. The FAA subsequently issued an Airworthiness Directive to fire-harden the waste paper towel disposal compartments, and later to ban smoking in lavatories.

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The primary concerns of an accessible in-flight fire are early detection and prompt extinguishment. Since the large majority of ignition sources are small, complete extinguishment usually can be effected. Passengers and crewmembers, visually or by smell, can usually detect the presence of a fire in its early stages. However, detection of a fire does not always imply knowledge of its exact location to allow for effective extinguishment. There is a possibility, perhaps remote, that the exact location of a fire may remain undetectable for a dangerously long period of time in hidden areas such as behind sidewall paneling or above the drop ceiling.

If an accessible in-flight fire cannot be extinguished by hand, means must be provided for fire containment until the aircraft can be safely landed. For overwater flights, the time period involved may be several hours. Containment can be accomplished by use of fire barrier materials (e.g., materials which have high char formation characteristics) in the compartment of interest. Research has demonstrated that lavatories constructed of fire barrier materials can contain severe fires resulting from burning plastic bags containing passenger service trash. By the same token, a lavatory fire detection and total flooding extinguishment system would also be effective in this application. Similar considerations exist for cargo compartment fire containment or suppression.

Some types of the aforementioned in-flight fires will be ventilation controlled and thus will undergo nonflaming pyrolysis. Just as with flaming combustion, this mode can produce toxic combustion products and dense smoke. Except for a jet transport accident on July 11, 1973, near Paris, France there is no record of an occurrence of this sort. (Editor's Note: As this report is submitted, and additional in-flight fire accident occurred in the Midddle East, killing all aboard. Investigation is underway at this time.)

Postcrash Fire - Although postcrash aircraft fires encompass a multiplicity of scenarios, most result initially from fuel spillage caused by wing separation, engine separation and/or fuel tank rupture (ref. 12). Occurrence of fuel spillage does not necessarily result in fire.

However, as high velocity air flows past liquid fuel emerging from leaking structures during a crash deceleration, fuel mist is readily formed. Clouds of fuel mist may be highly flammable, even with the fuel temperature well below its flashpoint, and may be ignited from hot engine parts, friction sparks, electrical sparks, and hot electric wires. The resulting mist fireball can then readily ignite a pool of released liquid fuel which may continue to burn if most of its surface is ignited. Once this happens, the temperature of the bulk fuel will progressively increase as burning continues, resulting in self-accelerating intensity of burning. Pool fire heating of intact fuel tanks may result in explosions leading to instantaneous fire intensification.

A typical survivable postcrash fire scenario involves exposure of an essentially intact passenger compartment to a large external fuel fire. Crash damage to the cabin in the survivable crash is normally limited to cracks and one or more small, door-sized openings. Although convective and radiative transfer of heat from the fuel fire to the fuselage is highly dependent on wind direction, a fully developed hydrocarbon pool fire can produce heat fluxes as high as 16-18 Btu/ft.^{2}-sec. Thus, cabin interior materials, cargo and passenger baggage

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may be subjected to rapidly increasing temperatures as well as to open flames penetrating fuselage openings. Commercial aircraft contain a variety of organic/polymeric materials capable of both thermal decomposition and flaming combustion. These include urethane foam seat cushioning, various upholstery fabrics, carpeting; blankets; structural and decorative molded plastics; paneling and interior finishing; luggage; clothing materials; and a wide variety of paper products. Although most cabin interior finish materials are flame-resistant when exposed to a small ignition source, upon exposure to a major fire, they can undergo thermal decomposition and burn. Carry-on items, clothing and paper products are rarely fire-resistant.

The major concern in the survivable postcrash fire is the ability of cabin occupants to evacuate rapidly.

There are three principal factors preventing escape of occupants from a postcrash aircraft fire which may be attributable to fire, rather than to the crash itself. These are heat, obscuration of vision due to smoke, and incapacitation due to inhalation of hot, irritant or toxic gases. All these factors will influence escape capabilities in varying degrees, depending on the nature, intensity, and extent of the postcrash fire. Thus, fire dynamics or the rates of development of flames, heat, smoke and hot toxic gases play significant roles in determining escape time. Fire dynamics and the resulting development of hazard depend on many factors, among which are the following:

a. Resistance to flame penetration and fire barrier properties of materials. (Note: Accident experience and large-scale fire tests indicate that the resistance of wide body aircraft to external fuel fire burnthrough is greater than that of the older standard body aircraft.)

b. Physio-chemical properties of materials; e.g., thermal diffusivity, ignition susceptibility, oxygen index, flash fire properties;

c. Influences on flame spread rate of materials, including flame height, stoichiometry, buoyancy and entrainment (combustion aerodynamics);

d. Heat, smoke, and combustion gas release rate of materials as a function of time and heat flux;

e. Location of materials relative to ignition source;

f. Geometry and configuration of flammable materials;

g. Area and weight of flammable materials;

h. Ventilation rate and direction;

i. Radiation exchange;

j. Wall and furnishings heat sink properties; and

k. Burning ceiling drippings and collapsing ceiling materials possibly igniting seats and carpet or inflicting serious burns on escaping occupants.

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The postcrash fire is an uncontrolled, unsteady-state reaction system characterized by high heat release rates and mass loss rates. Time to reach a hazard condition is a function of the accumulation (fire intensity) rate of the overall system. The time sequence of events from initiation of the fire plays an important role in determing the variation in fire intensity and hence the hazard level. In general, times to reach hazardous or untenable levels are quite short, usually a matter of a few minutes or less.

Under the demands of rapid escape from a postcrash fire, the concepts of toxicological and behavioral incapacitation, rather than death, are extremely relevant. Escape from the aircraft in a postcrash fire scenario requires that personnel be neither incapacitated nor disoriented from exposure to toxic and noxious gases over a relatively short time period of 2 to 3 minutes. The current knowledge of smoke toxicity provides little information on the potentially incapacitating effects of smoke inhalation by humans involved in a rapidly developing fire scenario.

Although it has been reported that approximately 15 percent of the fatalities in all jet transport accidents are attributable to fire or its effects (ref. 13), it is unclear as to what is the relative importance of burning fuel and burning materials on the ability of cabin occupants to escape. In order to answer this pressing question, full-scale and model experiments are underway using a fire scenario consisting of an intact fuselage with a door-size opening adjacent to a large external fuel fire (ref. 15 and 16). Results obtained with the cabin devoid of interior materials characterize the cabin hazards when the fuel fire is dominant. The following summarizes the outstanding findings:

a. Significant stratification of heat, smoke, and combustion gases; (some implications are the obscuration of ceiling mounted emergency lighting and exit signs and more severe heat exposure of materials at or near the ceiling in contrast to those materials located closer to the floor.)

b. The overriding importance of wind speed and direction and location of door openings on the rate of cabin hazard development;

c. Life threatening temperatures, dense black smoke but innocuous concentrations of carbon monoxide and minimal depletion of oxygen under conditions of penetration by fuel fire; and

d. Under quiescent wind conditions, heat flux levels of 14 Btu/ft^2-sec at the fire door rapidly dropping off away from the fire (less than 2 Btu/ft^2-sec at a distance of about 10 feet).

Other factors of undetermined significance are the materials on a fully boarded 270 passenger aircraft indicates that 17-25 percent are materials worn or carried on board by passengers (ref. 9, also see Volume II). Although this figure constitutes a significant percentage, it is unlikely, for several reasons, that these uncontrolled materials constitute a major fire threat on board a wide body jet. Foremost is that placement of passenger carry-on items inside overhead stowage bins, beneath seats, or inside closets makes it unlikely that these materials will experience significant fire involvement compared to regulated furnishing and lining materials. Secondly, because of the natural

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instinct of cabin occupants to move away from fire, it is unlikely that combustion products produced by clothing worn by occupants overcome by and eventually engulfed in fire will affect the ability of any remaining occupants to escape. The contribution to the overall fire hazard of passenger carry-on and airline-furnished passenger service items placed in open hat racks has not been documented.

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III

FIREWORTHY MATERIALS

Present Materials

It is important to emphasize that over the years there have been improvements in cabin interior materials, some required by regulation, others incorporated voluntarily by the airframe manufacturers.

Older transport airplanes, except the wide bodies, were designed to pre 1967 standards. When FAR Part 25.853 was first adopted in September 1967, most narrow body airplanes manufactured after that date were manufactured at least to that standard. FAR Part 121.312 required that any airplanes not meeting that standard were to be upgraded at the first major cabin overhaul or refurbishment. FAR Part 25.853 was upgraded in 1972; however, these upgraded requirements had already been applied to the wide bodies voluntarily by the aircraft manufacturers and were reflected in related special conditions by the FAA.

Presently all narrow body aircraft meet or exceed the 1967 standards in FAR Part 25.853. Many meet, partially meet, or exceed the so-called wide body standards of 1972 as now contained in FAR Part 25.853. All wide body airplanes meet or exceed the 1972 standards in FAR Part 25.853.

The materials used in wide body cabin interiors, based on accident data, are quite flame resistant. Wide-body lavatory configurations can and have contained fires both in test and in real situations; post-crash fires fueled only by the interior materials have not spread through the cabins; likewise there is no recent wide body accident evidence that any person has been adversely affected by smoke and toxic fumes from burning interior materials (See Editor's Note in Part II).

Aircraft accident records indicate that present regulations and voluntary upgrading have improved interior materials. This leads to two conclusions. First, current burn and smoke test methods provide the designer with a reasonable guideline for the selection of materials. A major difficulty lies in trying to judge the effectiveness of a particular candidate improvement relative to the overall safety of the aircraft. Current research programs will help to enlighten and resolve this question. Second, a definite improvement in materials has occurred and will continue to occur with each new generation of aircraft. To put the fireworthiness of current aircraft materials in proper perspective, most materials used in homes, offices and contemporary ground transportation vehicles would not be acceptable for use in aircraft despite their low cost and excellent performance characteristics.

Acknowledging the Fuel Fire

Interior construction materials exhibit substantial resistance to ignition. In a post-crash situation, the fire threat to the aircraft is the engine fuel

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that it carries. When fuel is not ignited, post-crash fires of significance do not occur. If fuel fires could be eliminated, further efforts to improve fireworthiness of interior materials would be less important. This has led to research and development programs aimed at controlling fuel fires by employing fuel additives and improving the standard integrity of fuel tanks and fuel systems under crash loads.

Advanced Materials

When considering material improvements, the severity of the fire threat must be taken into account. The threat from interior in-flight fires is much less than from post-crash fuel fires. Aircraft service records and engineering test data substantiate that current materials have resisted the in-flight fires (See Editor's Note in Part II).
Organic materials carried on-board the aircraft by the passengers are seldom flame resistant.

A material which shows promise for improved fire properties cannot always be used because of other factors such as strength, cleanability, cost, density, rigidity, produceability, formability, bonding or attachment characteristics, aging characteristics, thermal properties, sensitivity to solvents, and wear and abrasion characteristics. Incorporation of one new material may require developing an entire new construction philosophy for the aircraft subsystem on which it will be employed (i.e., sidewalls, ceiling and/or interior furnishings). In addition, FAA regulatory proceedings can stimulate efforts to advance the state-of-the-art. This has been demonstrated by the technical community's response to FAA rulemaking proposals with respect to the emission of smoke and toxic gases in post-crash fires.

Until we can significantly reduce the likelihood of a fuel-fed fire in a post-crash scenario, the ultimate goal for fire-resistant cabin materials would be to withstand high heat flux levels for extended periods of time. These flux levels can melt the aluminum outer skin of the aircraft, thus exposing the interior insulations and sidewalls. Recent accident and test data have been shown that current insulation and cabin sidewalls are capable of withstanding burn-through for times commensurate with evacuation. But for the long term, materials and materials systems (i.e. ablative and paint systems) should be developed which minimize heat release, smoke production and toxic gas and also provide maximum fire ablation in the presence of the heating rates to which they might be exposed.

Laboratory and full-scale tests indicate that fire containment benefits can be derived from improvements in the fire hardness of transparent window materials. A new fire-resistant NASA-developed epoxy-borazene transparent material has been demonstrated to reduce the hazard of fire penetration resulting from the failure of conventional acrylic window materials. Additional development will be necessary to ready this new material for production. It will require the further preparation and study of composite transparencies, an improvement in edge attachment technology and a reduction of the material's sensitivity to production solvents.

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There appears to be little prospect of introducing safer fabrics for carpet and upholstery in the near future. Although more flame resistant fibers are available, each has specific deficiencies which preclude use in this application. It has been demonstrated recently that it may be possible to achieve a reduction or elimination of the threat of fire spread throughout the aircraft by using a fire-blocking layer comprising a high-char yield elastomeric foam to protect the polyurethane foam in current passenger seats. This modification may produce a substantial reduction in fire spread combustion products and would provide more time for egress.

In summary, improvements within the state-of-the-art with windows, seats and escape slides that could reduce the threat to human life in a post-crash condition are possible in the short-to-moderate term.

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IV

TOXICITY AND SMOKE

Identification of the Problem

Concerns over the life hazards from combustion products (radiant heat, heated atmosphere, oxygen depletion, visual obscuration and toxic components) from cabin interior materials are related to the impact-survivable accident that is accompanied, or immediately followed, by fire. The primary source of this fire is the residual powerplant fuel that has spilled from one or more fuel tanks as a result of mechanical rupture during crash impact. This fire alone may seriously impede, or even prevent, the successful evacuation of individuals who have survived the impact in a functional state; in such cases the properties of interior materials may be of little significance to the overall survival rate. Therefore, it is only for the impact-survivable accident in which the size and intensity of the exterior fuel fire is not immediately life-threatening that the potential effect of interior materials on a successful evacuation is significant.

Of these hazards, there is no general agreement on the approximate magnitude (statistical) of the toxic contribution from burning interior materials, nor even agreement that such a problem exists to <u>any</u> degree-- in the case of an aircraft postcrash fire. Previous attempts to assess the role of interior materials from accident investigation data have led to contradictory conclusions or to the impasse that no conclusion, one way or the other, could be justified. See Attachment in Volume II for an approach to resolving the problem.

Reduction of the intensity of the fuel fire by fuel modification and the use of fuel containment systems would also greatly reduce the heat, smoke, and toxic hazard
for an aircraft postcrash fire. Since this is a scenario in which the time available for successful evacuation is usually limited to a few minutes, any action that would delay the initiation, or the subsequent rate, of thermal decomposition of a material would obviously extend the escape time available before a toxic incapacitation environment is produced. Therefore, the use of materials with improved flammability and smoke characteristics may also accomplish the added dividend of reducing the toxic <u>hazard</u> for an aircraft postcrash fire.

Projected Time Frame Needed to Deal With the Problem

The key for resolution of this problem is the development of a valid and practical approach to life hazard evaluation. Work under way to define the toxic potential of cabin materials in a form useful in fire modeling efforts could lead to a valid toxic hazard evaluation technique. Similar efforts are underway in hazard evaluation using room fire and building fire modeling studies. Solution of this problem, if appropriate effort is applied, is about 5 to 10 years away. Work should continue on the definition of the potential of the other life hazards (listed under identification of the problem) for use in fire modeling.

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Toxicity, Toxic Hazard, and Risk

In today's world of sophisticated science, it is unfortunately common for public officials, the information media, and the general public to misunderstand scientific findings. Historically, this has been the case in the area of toxicology. As a consequence, there is an increasing responsibility for scientists, and in particular for toxicologists, to extend their active involvement into the arenas of public enlightnment and the formulation of laws or regulations that pertain to public health and safety.
A prime concern for toxicologists is the apparent confusion that often exists for nonspecialists between the terms "toxicity" and "toxic hazard." Toxicity is a specific property of any, and all, chemical species -- or of any more-or-less defined mixture of species. It is expressed as that quantity of the chemical (mixture) just sufficient to bring about some specific, undesireable change in the well-being of a living organism, when that chemical is administered over a defined interval of time and under specified conditions. It is almost a biological axiom, and one that is not always fully appreciated, that any chemical, natural or synthetic, is potentially toxic; it needs only to be administered in sufficient quantity over a sufficient period of time and under appropriate circumstances to have detrimental effects on any organism.

Some of the various ways in which the toxicity of a specific chemical could be stated are illustrated by the following:

(a) An approximate lethal oral dose of hydrogen cyanide (HCN) for a typical male adult human is 100 milligrams.

(b) A lethal oral dose of HCN for an average rat is one-third of a milligram, or 330 micrograms.

(c) The concentration of carbon monoxide in air that would physically incapacitate a mouse in 5 minutes is approximately 2,000 parts-per-million.

So, it is obvious that toxicity is a measure of how much of a substance would be required to produce some specified undesirable effect in a given biological species when administered in a particular manner.

This brings us to the concept of toxic hazard, the determination of which is simply an appplied "science" based on the accepted fact that any given chemical is potentially toxic. While this established toxicity is a property of the chemical under specified and controlled conditions, its toxic hazard is an evaluation of the degree of harm that could result to the same organism from an exposure to the maximum amount of the chemical reasonably expected to be present in some defined, but entirely different, set of circumstances. Normally this new environment would be some natural setting such as the home, the workplace, a vehicle, etc. Thus an estimate of a toxic hazard is not only dependent on the factual knowledge of how toxic a chemical is under standard laboratory conditions, but must also take into account the effects of an entirely new set of environmental conditions and circumstances as well as a probability estimate of how much chemical will be available as a function of the exposure time.

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In a given environment the potential toxicity may not represent a hazard for any of several reasons; the quantity is inadequate; the time interval over which it is acquired is too long; or other existing conditions are sufficiently different from those for which the toxicity was defined that the chemical is prevented from exerting its harmful effect. Indeed, toxic effects result from only an infinitesimally small fraction of the daily encounters between living organisms and toxic agents; otherwise the myriad of chemicals we breathe, ingest, wear, touch, and otherwise immerse ourselves in would have exterminated us long ago!

Theoretically, at least, assessment of toxicity for a given pair of chemical and biological species could be performed only once and never need repeating, except possibly for verification of the original results. This assessment would be an activity limited almost exclusively to scientific specialists and conducted in well-equipped laboratories under specifically defined and well-controlled conditions.

Hazard assessments, on the other hand, could be required for each separate occasion for which that one chemical could possibly co-exist intimately with a living organism. Thus, toxic hazards are a potential threat in any and all environments, and the decision as to whether or not a hazard does exist is dependent on knowledge of the toxicity of the chemical, the nature of the organism, and the specifics of their mutual environment. The assessment of hazard is also an activity that should be the exclusive responsibility of the scientifically trained experts. The results can be no more meaningful than the scientific knowledge, the expertise, and the practical experience that can be brought to bear on the solution.

The following are examples of the types of excercises in logic that might be undertaken in distinguishing between the toxicity of a material and the potential degree of hazard associated with its use in a certain way in a specific environment.

Hydrogen cyanide is a highly-toxic, gaseous chemical, as was noted above. This does not mean, however, that any situation in which a person might inhale some HCN, or ingest one of its solid salts, is automatically a highly hazardous one.

The smoke from burning tobacco is known to contain HCN; therefore one might ask if any tobacco-containing products are cyanide hazards. Obviously there could be a host of proper responses to such a question, depending on the remaining, unspecified circumstances.

How much of a hazard would a drying shed half-filled with 1000 pounds of tobacco represent? Absolutely no hazard from cyanide -- not as it stands. What are the chances that it could be unintentionally ignited, and what is the cyanide hazard for this new situation? Well, how far removed are the nearest living organisms of any concern? What is the direction of the wind? Its velocity? Where is the smoke going and how rapidly is it being diluted? What would be the respective hazards for three individuals who entered the burning shed to fight the fire -- one breathing through a mask equipped with a particle (dust) filter, one wearing a full-faced, self-contained breathing apparatus, and the third with no respiratory protection at all?

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The above are meant to illustrate more explicitly that a determination of hazard level encompasses the concepts of: hazard from what, specifically; under what circumstances; and in what environment? One last illustration may help clarify the element: hazard from what? Although the smoking of one cigar would not represent for the smoker, a significantly hazardous exposure to hydrogen cyanide, consider a slightly different question. How much of a hazard to oncoming traffic, at night on a two-lane highway, would you assign to the situation of a car driven by a newly-licensed teenager who had just finished smoking his very first cigar -- inhaling every draw? (For those who ever experienced those dramatic effects of their first cigar, or cigarette, the answer is surely obvious.)

There is, however, an additional judgmental activity in which the politician, the bureaucrat, the social expert, the economist, and even citizens generally should play an active role. This is the determination, for those areas controlled or regulated by government, of the level at which a predicated degree of hazard no longer represents an "acceptable risk" and becomes an unacceptable one. In reality, the assignment of a degree to a pre-determined hazard level is by far the most difficult and the least objective of the three types of evaluation.

Yet, such an evaluation is important. The concept of absolute safety or zero risk is an artifical one and has not been experienced by mankind, at least where natural forces are involved. Moreover, not all situations can be rendered absolutory safe at any cost. It is useful to determine whether small-risk levels are achievable and, if so, at what cost, recongnizing that quantifying risks and benefits of pariticular courses is an exact science, although one which can be helpful to policy-makers in the exercise of their judgement.

Inhalation Toxicity Testing

(1) Background. Over the years, a more-or-less standardized technique has evolved for evaluating the toxicity of a given agent. Under defined and repeatable conditions, a known weight or volume of the solid or liquid test substance is administered to an animal of known weight. The selected route of administration can be one of several choices:

(a) Oral

(b) Parenteral (by injection or topically)

(c) Inhalation

Administration by the selected route will be repeated in a number of animals all at the same dose level, i.e., quantity of substance per unit of body weight. Additional groups of animals will be given successively higher dose levels and then all will be observed for a prescribed period of time. From the observed responses to the different treatment levels a dose-response curve can be constructed. This curve, or plot, will reflect the percentage of each test group of animals that gave the required response when administered each of the dose levels. From such a plot can be derived an estimate of the quantity of toxic agent that produced the observed response in one-half of the tested subjects. This quantity is commonly called the "effective dose for 50-percent response," or ED_{50}.

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An important requirement for determination of an ED_{50} is knowledge of the quantity and identity of the toxic agent that the test subject received. This is not too difficult to accomplish for a toxic substance that is either a solid or liquid, and that can be administered by one of the usual routes. But consider the case of a gaseous agent that is acquired by inhalation. A different set of criteria must be formulated for this special situation, for obviously one cannot administer a fixed, known amount of a gas to each subject. Of these routes of administration, inhalation effects are of primary concern in post-crash fires. The usual procedure in inhalation toxicology is to establish a known concentration of the test agent in air and introduce the test animals into this atmosphere for a specified time interval. Repeated exposures of additional groups at different concentrations, but for the same time period, will supply the data for relating the percent of each exposed population that exhibits the desired response to that exposure concentration. Thus we obtain, not an effective dose, but an effective concentration for 50 percent response-- an EC_{50}. In this case, however, we also must specify the duration of the exposure; therefore, if exposure were for 60 minutes we would obtain a "60-minute EC_{50}."

It should be immediately evident that the values for an EC_{50} will change as the duration of the exposure changes. The atmospheric concentration required to kill a rat in a 5-minute exposure must surely be greater than that needed to kill in 30 or 60 minutes. Thus the value of EC_{50} is normally inversely related to the duration of the exposure, but not necessarily inversely proportional to it.

(2) Use of animals vs chemical analysis. Chemical analysis of combustion atmospheres is an integral part of toxicity tesing and subsequent hazard analysis. However, analytical procedures should be used to enhance the value of animal data rather than in lieu of animal data.

Most commonly used analytical procedures allow for identification and quantification of from one to several of the principal off-gases that are generated during combustion or pyrolysis of a material. In no case however, can a combustion atmosphere be completely characterized both qualitatively and quantitatively. Toxicity, in inhalation testing, is a function of exposure time and concentration and is manifest in the whole animal. For atmospheres of single, pure gases, toxicity may be predicted on the basis of analytical data once the toxicity of the pure gas has been determined. For atmosphere comprised of two gases, toxicity can often be predicted if the toxicity of each individual gas is known as a function of time and concentration. For atmospheres containing three or more principal gases toxicity can rarely be predicted- even if the toxicity of all the principal gases is known. Since combustion atmospheres usually consist of many components, identification and quantification is a laborious and costly procedure. By inhalation toxicology, using animals, one can evaluate the combined toxic properties of the entire mixture and determine whether further component identification effort is warranted.

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(3) Extrapolation of animal data to humans. Animal toxicity data are almost always used as the basis for establishing safe exposure concentrations for humans. Quite obviously though, there are cases in which animal data are not predictive for the human. In general, it is safe to state that extrapolation of acute-lethal animal toxicity data is more reliable than is extrapolation of chronic effects data--even though there will be differences in susceptibility--or tolerance--among various species. Since exposure of humans to combustion/pyrolysis atmospheres is principally an acute situation, it should be reasonable to extrapolate actual animal results to the human situation, provided the appropriate scaling factors are utilized.

Incapacitation vs Mortality as a Response Criterion

The impact-survivable, postcrash aircraft fire presents a unique environment to the surviving passengers and crew who are attempting to evacuate to safer surroundings. In most such accidents the time available for successful evacuation is in the range of possibly 2 to 5 minutes depending on the intensity of the fuel fire. Even for accidents that occur on or near airports, this time is usually too brief for crash rescue personnel to arrive at the scene and physically remove any individuals from inside the aircraft. Historical review of these accidents also reveals that rarely is a passenger able to physically remove a fellow passenger who cannot, or will not, leave the aircraft on his own. Consequently, it appears that a passenger who does not get himself out, does not get out.

The relevant toxicological question then becomes one of what physiological condition for a passenger most closely describes the loss of his ability to exit the aircraft under his own power. Any incapacitation due to physical or mechanical trauma will not be considered since we are concerned in this instance with only those individuals who survive the impact in a functional state and are then rendered nonfunctional by exposure of toxic gases. Incapacitation could also result from the heat stress, loss of vision due to smoke, or sheer panic, as well as from toxicological effects.

It is surely obvious that at some physiologically-impaired state, short of death, a person would be physically incapacitated. An unconscious person would certainly be incapacitated; on the other hand, one might be still conscious and yet be unable to muster the psychomotor coordination necessary to escape. Therefore, as was first proposed by CAMI scientists, the desired endpoint for an animal toxicity test that would relate to loss of escape potential from a burning aircraft should measure the earliest occurrence of physical incapacitation. Further research is in progress to determine the most suitable methodology for measuring this incapacitation.

There is an additional concept that is worth discussing. Interest in the toxicity of the combustion products present during evacuation is primarily a question of the relative toxic threat. Whatever the toxic threat from materials in current use, could that threat be justifiably reduced by substituting other materials? Therefore, we are interested in comparing the

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relative toxic threat among two or more materials that could be used for the same purpose. Furthermore, this toxic threat should be in terms of the time available for successful escape.

So, we are really interested in measuring the relative times-to-incapacitation that result from exposure to smoke from these materials. It is obvious that for any toxic gas the lethal exposure time will be longer than the incapacitating exposure time, and as a consequence any relative mortality data might not properly reflect the relative times available for escape.

The Relevance of Laboratory Test Results to Cabin Fires.

Toxic hazard, as was discussed in an earlier section, is an evaluation that can be made only after some type of specific, quantitative toxicity information is available. In the context of combustion product toxicity, however, there are some unique difficulties in attempting to predict toxic hazard for a real fire environment, even from known toxicity measurements on the same materials, if those measurements were made with a small-scale test system.

The type of information that one needs, in order to reduce the toxic element of the fire hazard from cabin interior materials, is whether or not there are differences among the toxic hazards of candidate materials for a given application, structure or use.

Several techniques are available for generating this information from small-scale laboratory tests. In a closed system of known volume (or a flow-through system of known flow rate) one could determine the weight of each material that would have to be burned for the resultant smoke to incapacitate one-half of the animals in 10 minutes (a 10-minute ED_{50}, where D is "dose" and is synonymous with weight of material). Alternatively one could experimentally define time to incapacitation as a function of weight of burned material.
We would then know which of the three materials produced the most-toxic smoke and which the least-toxic, but how do we relate these results to the real cabin fires? These values are only toxicity measurements, and we have already discussed the problems associated with converting from toxicity data to toxic-hazard evaluations. Unfortunately, there are even more problems than just those associated with these conversions. Even if all parameters other than toxicity were assumed to be constant in the cabin fire, for each of the materials, we still might not be able to effect a reliable conversion for the following reason.

If the composition of the toxic components in the smoke from the cabin fire were the same as in the laboratory test smoke, then obviously knowledge concerning one could be used to predict effects of the other. In reality, this is very unlikely to be the case.

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Investigations with small-scale tests have shown that the composition, and thus the toxicity, of the smoke from many thermally-decomposing materials is very sensitive to the test conditions. Two parameters that seem most influential are the environmental temperature, or the heat flux, at which the decomposition is effected, and the ventilation rate relative to the decomposition rate of the material.

One obvious physical manifestation of the effect of these two parameters is whether a material decomposes with or without flaming. The resultant combustion products, and therefore the toxicity, can vary with these parameters to the extent that under one set of conditions it is highly toxic and under another set is almost nontoxic.

This potential lack of identity, or conformance, between the test combustion products and the cabin fire combustion products is a well-recognized problem, and one which scientists have made several suggestions for solving. The most realistic and meaningful way is to measure the toxic effects from large-scale fires. However, this approach is the most expensive and, therefore, limited in use.

Another possible approach is to "burn" the test material in small-scale tests under exactly the same thermal and ventilation conditions as would be found in the real fire. Unfortunately, there is no single real fire; all fires are extremely variable, not only from fire to fire, but even within the time course of a single fire. One could probably observe the entire spectrum of all possible conditions both among several fires and even within any specific fire. Some engineers have suggested that a "standard fire" simply be defined arbitrarily, then small-scale test conditions could be assigned fixed values based on that standard; others, however, have been reluctant to accept this approach for fear that material regulation based on such a philosophy could as easily increase the cabin fire toxic hazard as decrease it.

A third approach utilizes the concept of a "worst-case condition." If the toxicity of smoke from a given material can vary as a function of "how it is burned," then obviously some one set of conditions will produce the most-toxic smoke possible. The real fire may also, at some time, expose the material to this worst-case set of conditions. Therefore, the specific toxicity for each material, that would be utilized for extrapolation to its potential toxic hazard in a fire, would be the maximum toxicity obtainable for that material by varying the conditions in the small-scale test over the range that could be expected in a real fire. The worst case in specific toxicity, however, does not necessarily represent the worst case in toxic hazard.

There has been no mutual agreement, to date, as to which approach, if any, could be utilized as a basis for material regulation, but, no matter what technique might eventually be approved, there is an important point that needs to be reemphasized. Materials should never be regulated solely on the basis of the specific toxicity of their thermal decomposition products, but according to their toxic hazard, which includes other material property variables and specific use conditions in the aircraft cabin.

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There is one additional controversy that is pertinent to this discussion. Should the toxic hazards for competing materials be expressed in absolute or relative terms? Would it be sufficient to know that material C has three times the toxic hazard of material A, and that A has twice the toxic hazard of B? Or must one be able to say that, as they are used in the cabin, B would allow 12 minutes for escape before the average passenger would become incapacitated, while A would allow 6 minutes and C only 2 minutes? These are very different questions and the research required to obtain the respective types of data is also quite different. The decision must be made, however, before the experimental research is designed.

Visual Obscuration Due to Smoke

In addition to the toxic effects of inhaled combustion products, there is another property that can increase the evacuation time from a cabin. This is the visual impairment produced by the irritant properties of the smoke and the decreased transmission of light through the smoky atmosphere. Any increase in the time required for evacuation prolongs the exposure to heat and toxic gases and therefore reduces the likelihood of escape.

Decreased visual effectiveness can obscure aisles, exits, exit lights (particularly those in the upper portion of the cabin), obstructions (such as displaced carry-on items, service items, cabin structures, or even bodies); can produced disorientation sufficient to cause passengers to go in the wrong direction or open the wrong exit; and could even induce panic in some individuals (Ref. 20).
Although such effects from smoke are obvious and would logically affect evacuation time, a dependable correlation between quantity (density and nature) of smoke and its quantitative effect on evacuation time has not been established experimentally. Such experiments are in progress, however, and better information should become available--subject, or course, to the hazard limits that control the design of any research that utilizes human subjects.

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V

FUEL SYSTEM FIRE HAZARD REDUCTION

The major source of energy in post crash aircraft fires is the airplane fuel supply. In fact, if there is no airplane fuel fire, almost invariably no fire of any significance develops. Consequently, developing a means of minimizing the contribution of this fuel to post crash fires is of prime importance. In doing this, however, the overall aircraft safety on the ground and in flight must not be compromised. The application of this philosophy to commercial aircraft design over the past three decades has resulted in an excellent safety record. It is incumbent upon the industry that this practice be continued and that it be the paramount consideration when evaluating system designs intended to reduce the fire hazard in survivable crashes.

An assessment of current design practices in this regard is reviewed in light of operational experience in the following paragraphs. Alternative approaches to reduce the post crash fire potential are described and evaluated in terms of an overall airplane safety effectiveness. Finally, the adequacy of current Federal Aviation Regulations and the need for more research and development in specific areas are discussed.

Assessment of Current Design Adequacy
Current Design Practice

The design philosophy which has for so many years resulted in an excellent fire safety record for the aircraft industry has been to isolate the aircraft fuel from potential ignition sources. This isolation is fundamental to fire prevention. Very specific fire safety design requirements are stated in the Federal Aviation Regulations requiring the aircraft industry to expend a considerable portion of its development effort to comply with these regulations. However, since an excellent safety record by the industry is mandatory to maintaining the goodwill of the traveling public, the design requirements dictated by the regulations are often exceeded.

The application of these regulations fall into three major categories: powerplant fire protection, fuel system fire protection, and fuel tank crashworthiness. Powerplant fire protection puts heavy emphasis on the isolation of ignition sources since the power source areas involve hot engine parts and components that are converting fuel energy to useful work. Accidental fires are localized by firewalls which isolate them from adjacent fuel tank areas. Lines and components containing combustible fluids are required to use fire-resistant materials to protect their contents from fire involvement. Potential leakage areas are shrouded and drained to areas which are free of ignition sources. Fuel supplied from the fuel tanks may be isolated from the power source areas by means of shutoff valves in the event of engine fires. Fire detection and extinguishing systems are used to control fires which may start in high fire potential areas. All of these capabilities must be demonstrated according to Federal Air Regulations prior to certification by the FAA.

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In the multicomponent fuel system, each component receives fire protection consideration to achieve a high level of safety for the overall system. Spaces adjacent to fuel tanks incorporate drains protected by flame arrestors and are air purged to prevent the buildup of combustible mixtures. Component temperatures in fuel tanks are maintained at a low level and electrical parts are made explosion proof.

In the event of a wheels-up landing, special design measures are taken to protect the fuel system components from damage which may release fuel. Components and fuel lines are located where they are protected by the basic aircraft structure. Where the relative motion of the aircraft structure in survivable crashes could cause fuel lines to part within the fuselage area, fuel lines capable of stretching as much as 50% of their installed length, are employed to absorb impact and relative motion without leaking. The capability of exhibiting a reasonable degree of deformation and stretching without leakage must be demonstrated during certification.

Fuel shutoff valves, which are provided in the fuel lines to each engine and auxiliary power unit (APU), are often duplicated for increased reliability in the isolation of fuel from potential ignition sources. These valves are located at the fuel tank boundaries so that they are not affected by line damage. Open flow fuel tank vents are provided for each tank to maintain the tank vapor space at or near outside ambient pressure for all conditions of flight. The utilization of unpressurized tanks in commercial jet aircraft eliminates the potential of pressurization component failures which can subject the tanks to excessive burst and collapsing pressures in the event of failures during ascent or descent. Flame arrestors or other means are provided in most transport category aircraft to preclude external fires from entering the vent line and igniting vapors within the fuel tank.

In the wing fuel tank areas, such hardware as landing gear, wing flaps, and engines are designed to fail in a break-away manner without compromising the wing structural integrity to maximize fuel tank crashworthiness. Fuel tanks within the fuselage receive special attention in this regard. While they are designed to withstand emergency landing loads, standard design practice dictates that they have greater than the minimum required strength. A heavy outer shell is provided in addition to the basic aircraft structure and an innerbag to contain the fuel. Break-away, self-sealing couplings, or stretchable hoses are used to minimize fuel spillage in the event the tank is displaced from the connecting fuel lines by impact loads in survivable crashes.
By adhering to these design practices and incorporating new practices only after their worth has been proven by extensive testing, the industry has provided the traveling public a continuously decreasing rate of accidents involving fuel fires over the years.

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Operational Experience

Before evaluating potential improvements to fuel system design, it is appropriate to look at the accident record to define, if possible, the effectiveness of proposed design changes in reducing fatalities due to post-crash fuel fires. A summary of the accidents involving post-crash fuel tank explosions for the worldwide turbine-powered aircraft is shown in Figure 3. Note that these accidents include foreign carriers as well as two accidents for which there were no fatalities. The tank explosion accidents listed on Figure 3. are divided into two categories, those which involved minor damage so that the fuel tanks were initially undamaged and those accidents which resulted in massive impact damage causing tank rupture and subsequent massive ground fires. In the first category of accidents, two involved ground fires which propagated through the vent system, and two involved failure to stop fuel flow through a ruptured engine feed line. It is believed that the tank explosions could have been prevented or substantially delayed for these four cases by design changes which have since been developed.

Propagation of fire through the fuel vent can be delayed to permit passenger evacuation by the use of vent flame arrestors which have been developed for that purpose. Vent flame arrestors and suppressors are offered as standard or optional equipment on all large U.S. transports in current production.

Design changes in the fuel shutoff systems have been made to provide greater assurance of fuel cutoff under emergency conditions. In the 707 case, the fuel fire, fed from the ruptured fuel line, continued to burn because of failure to activate the spar fuel shutoff valve by pulling the fire shutoff handle. The throttle had previously been retarded to the engine-off position. These airplanes now incorporate actuation of the spar fuel shutoff valve by a fuel shutoff lever on the throttle quadrant as well as on the fire handle, thus providing increased assurance of shutoff valve actuation.

Returning to Fig. 3, the DC-8 accident at Anchorage involving fuselage breakup and ruptured fuel tanks occurred while overrunning the runway during an aborted takeoff. The fire started shortly before the airplane came to a stop. Sometime thereafter two or more large explosions occurred. Most of the passengers and crew (182) evacuated the airplane. However, 46 passengers and one stewardess were unable to escape. Presumably if the explosions (assumed to be fuel tank explosions) had not occurred, these 47 people could have also evacuated. It is possible that a fuel tank vent fire protection system or inerting system might have reduced the fatalities from this accident by delaying or preventing the explosions. A review of the remaining accident briefs does not indicate that any fuel tank anti-explosion system would have effectively reduced the fatalities in the remainder of the accidents which involved major airplane damage, large quantities of fuel spillage and subsequent fuel tank explosions.

Design Alternatives

The various design alternatives which have been considered for potential improvement of the post-crash hazard including fuel tank inerting, quenching, suppression, crash-resistant fuel tanks, anti-misting fuels, and alternate fuels are discussed in the following paragraphs. It should be noted that an evaluation of these alternatives inherently requires the consideration of their effect on the total airplane design and operation and is not limited to only post-crash considerations.

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World-Wide Turbine Powered Fleet

		Model	Year	Fatalities (All Causes)	Survivors	Hull Loss	Fuel	Potential Reduced Fatalities or Hull Damage: Vent Arrester or Suppressor	Potential Reduced Fatalities or Hull Damage: Improved Fuel Cutoff Systems	Potential Reduced Fatalities or Hull Damage: Fuel Tank Explosion Protection	Low Probability of Any System Benefit
Ground Fire-Minor Impact Damage	Rome	707	1964	48	25	Y	JP-4D	X		X	
	London	707	1968	5	121	Y	Kero.	X	X	X	
	Singapore	CMT	1964	0	68	Y	?	X		X	
	Stockton	DC-8	1969	0	5	Y	?	X	X	X	
	Anchorage	DC-8	1970	47	182	Y	Kero.	?		?	?
Massive Ground Fire	Monrovia	DC-8	1967	51	39	Y	?				X
	Cincinnati	880	1967	70	12	Y	Kero.				X
	Cincinnati	727	1965	58	4	Y	Kero.				X
	St. Thomas	727	1970	2	53	Y	Kero.				X
Wing Tank Breakup	Pago Pago	707	1974	97	4	Y	Kero.				X
	Nairobi	747	1974	59	97	Y	Kero.				X
	Tenerife	747	1977	335	61	Y	Kero.				X
Severe Body Damage	New Hope	DC-9	1977	62	23	Y	Kero.				X
	Wrightstown	L-382	1970	3	0	Y	Kero.				X
	New Haven	CV-580	1971	28	3	Y	Kero.				X

FIGURE 3
TANK EXPLOSION ACCIDENT ASSESSMENT
(POST CRASH FIRES)

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Fuel Tank Inerting

Fires within the fuel tank can be prevented if the oxygen concentration in the vapor space above the fuel is maintained below combustible limits by displacing part of the oxygen with an inert gas. Nitrogen is the most logical inertant. Nitrogen extraction from the air requires a complex separation system if the nitrogen is extracted in flight, or a costly and complex distribution/ handling system if the nitrogen is obtained by a ground operation and then carried onboard as a cryogenic liquid. The tank system, which is pressurized above outside ambient to preclude air from entering the tank, must accommodate vent relief valves and back up relief valves, pressure regulators, distribution lines, and a fuel "scrubbing" system. The latter is needed to remove the oxygen dissolved in the added fuel which would otherwise outgas oxygen during climb. The reliable functioning of these additional components must be assured if a decrease in overall system safety is to be avoided.

In the post-crash situation, a fuel tank inerting system could provide limited benefits depending upon the severity of the crash. In a massive wing breakup, little or no benefit would be available. In a minor wing breakup or no damage situation, the inerting system could provide some benefit. In either case, the system benefit would be reduced considerably if the source of agent were lost during the crash. In the case where little or no damage occurs to a particular tank, there has been considerable experimentation conducted to determine whether or not inerting will protect against an explosion from an under-wing fire. These tests by NAFEC (Reference 14) showed that it is possible for a very intense under-wing fire applied to an intact, unwetted tank surface to initiate an explosion and that inerting could prevent such an explosion. Even in this most intense underwing fire, the tests showed that no explosion took place until 95 seconds had lapsed. They also showed that in a less severe fire, particularly with modest fuel loads, the tank would self-inert, i.e., a slow oxidation would take place and the tank would become inert. It was concluded that, except for the case where a small tank penetration had occurred, fuel tank inerting did not provide any significant additional protection over existing vent protection systems in a post-crash fire situation.

At the 1977 Public Hearing, the Aerospace Industries Association of America projected that the cost of inerting, system acquisition and operation of the worldwide fleet would cost $19 billion through 1996, and would result in an additional 1.3 billion gallons of fuel usage over that period of time. Reference 13 presents a recent update of this evaluation which indicates the cost for a 20-year period has increased to $24 billion even though the system weight was decreased significantly from the original study (3460 lb to 1743 lbs for the 747 airplane, based on inputs from Parker-Hannifin Corporation). This lighter weight system is problematical in that it eliminates the second LN_2 storage tank system and therefore does not provide a fail safe operational system and would not meet the airlines' dispatch criteria. The projected cost increase mainly reflects an increase in fuel price (77¢/gal assumed vs 38¢) and inflation. Current estimates of jet fuel costs are far in excess of $1.00 per gallon, further escalating the cost of the inerting system. It should be noted that development and installation of certifiable, fail-safe operational systems for commercial aircraft requires at least 5-6 year time span.

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The concept of onboard inert gas generation (IGG) offers potential reduction of cost due to the elimination of the formidable logistic costs associated with ground-produced LN_2. The self-contained onboard generation of N_2 would provide an operational inerting system worldwide, thus freeing the airplane from dependence on LN_2 ground support equipment. The IGG system would use much of the component technology which has been developed for the LN_2 systems. Additional research and development would be needed in the area of onboard generation technology and systems application before it could be considered for commercial application (Ref. 15).

Fire Quenching

An alternative to fuel tank inerting is the installation of reticulated polyurethane foam or expanded metal foil in the fuel tanks. This passive system, depending on the porosity of the foam or foil, works by either flame arrestment and/or an energy absorption mechanism which prevents an excessive over-pressure or explosion from developing. While an internal tank fire is possible, the fire does not cause an explosion, and eventually self-extinguishes from lack of oxygen. While some degree of flame propagation is to be inherently expected, the reaction is of the low order, flash fire variety. Foam by itself or in conjunction with flexible bladders has been applied to military aircraft over the last 13 years for tank protection against lightning strikes, gun fire, and resulting explosions. Experience in combat situations is reported to be good.

However, a translation of this military need to the commercial theater presents difficulties. Due to its susceptability to hydrolysis, earlier foams in some cases experienced degradation when exposed to extremes in humidity and high temperature environments. Some military aircraft have utilized the same original foam for over 13 years. Development has continued and newer foams are not susceptible to hydrolytic degradation. Water accumulation in the foam at the tank bottom provides a perfect location for microbacterial growth and subsequent tank corrosion in wet wing configurations. Foam removal for periodic structural inspection may prohibitively increase maintenance cost.

System weight, weight of retained fuel from wetting and loss of fuel capacity displaced by the foam would present severe operating penalties on commercial aircraft. For a B-747, the combined weight penalty (foam and fuel wetting) is estimated at 14,000 lbs. This penalty assumes a 40% voided volume which is probably optimistic for the large size tanks. Lost fuel capacity varies from 0.75% to 2.0%, depending on the type of foam.

The military services have temporarily removed foam in some of the C-130 airplanes for some of the above reasons although they are currently in the process of installing the new improved hydrolytically stable foams in the C-130 fleet. Reticulated foam is being utilized in the majority of new combat aircraft.

In an accident situation, foam could provide protection in a "no or minor" wing damage situation. Little is known about its performance under external fire conditions.

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Although testing has not been performed, it is assumed that in massive wing break up, foam would not help since flammable fuel mists would be formed and structural damage would permit flame propagation around the foam and negate its effectiveness with respect to the damaged tanks. However, explosions in foam containing areas would be prevented.

Foams are categorized as potentially useful only in limited circumstances and they would impose a performance penalty and maintenance burden on the operators.

Much of the preceding discussion applies to an expanded aluminum foil mesh and will not be repeated. However, there are some significant differences which are discussed below.

Because of the higher melting point (1100° F) of foil, its performance under external fire conditions has been proven to be excellent. It is also hydrolytically stable, and when installed, does not encourage electrostatic discharge during fuel operations. In small transports problems associated with installation and removal due to its semi-rigid and non-collapsible characteristics can likely be overcome with proper engineering; however in large transports, aluminum foil mesh may be impractical because of the additional weight involved and possible need to redesign existing fuel systems.

Fire Suppression

The basic concept of this system is one in which the flame of an incipient explosion is sensed by a detector (IR or UV) which triggers the discharge of a fire extinguising agent to extinguish the fire before a hazardous overpressure can develop.

Expansion of the currently applied surge tank flame suppression system to a full-scale tank suppression system increases the system complexity by an order of magnitude or more. A typical aircraft system will involve two to eight or nine tanks, each of which will have a large number of bays. Since each bay would require one or more flame sensors, a typical system could have 50 or more sensors, and several discharge bottles and distribution plumbing. This presents an extremely difficult system to install and maintain. The sensitivity of the detectors makes the probability of inadvertent firing of the system likely during routine system maintenance or tank entry. The application of explosion suppression to commercial transport fuel tanks has been studied on numerous occasions. In all cases, the complexity of the installation prompted by the numerous detectors and suppressors overrode any potential value except in military aircraft. Even recent state of the art improvements which would significantly reduce the number of detectors has not shifted the balance in favor of installation. Retrofit of the system to existing aircraft in addition to the maintenance of the system after the one per aircraft per year actuation that presently occurs, would be prohibitive from an operator's standpoint. It is therefore concluded that explosion suppression applied to the fuel tank is not applicable for protection of commercial transports during crash conditions.

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The above systems were evaluated in terms of weight, cost, maintenance, reliability, retrofit capability, and effectiveness. The results of this evaluation are shown in Figure 4. In every category the incorporation of a vent line flame arrestor is rated as better than, or equivalent to, the more complex systems currently under discussion. Of the more complex systems, only the inerting system appears to offer some improvement in the post-crash fire environment. Again referring to Figure 3, of the 15 accidents involving post-crash explosions, inerting had the potential of reducing fatalities or hull damage in five cases. In four of these five cases, it is believed that the relatively simple approach of vent flame arrestors or suppressors or improved fuel cutoff would have been as effective as the inerting system. These simple and reliable systems are presently installed in most commercial transports. They are typical of the tried and proven fire protection designs which the aircraft industry has pursued throughout its history. Since 1962, this policy in jet transport design has resulted in a reduction in accidents involving fuel vapor explosions from 1.4 to approximately 0.1 per million departures (Figure 5).

From the above survey of existing and proposed methods to eliminate fires inside jet transport fuel tanks, the following conclusions were arrived at:

- An analysis of accident history indicates that existing fuel system fire protection methods are as effective as quenching and suppression systems and supply most of the protection offered by inerting in survivable accidents where minor wing tank damage occurs.
- Although quenching, suppression, and inerting systems may reduce the probability of explosions where intense external ground fires impact near empty but intact wing tanks, the increased complexity of these systems can compromise the inflight safety of the airplane in commercial applications.

- Quenching, suppression, and inerting systems represent large economic, operational, and maintenance penalties.

Crash-Resistant Fuel Tanks

The term "crash-resistant" fuel tank is generally associated with fuel tanks that are capable of remaining reasonably intact during a crash event, thereby eliminating or minimizing fuel spillage and the corresponding post-crash fire threat to surviving passengers. If achieved, this concept can eliminate most destructive external fires and complement the simple measures discussed in the previous section. The highly visible success of crash-resistant fuel systems installed in Army helicopters makes direct application of this technology to jet transport aircraft tempting. However, the obvious differences in aircraft characteristics, crash scenarios, and accident experience may dictate another course of action.

Summary Evaluation of Concepts

Concept	Weight	Cost	Maintenance	Reliability	Retrofit Capability	Effectiveness
Liquid N_2	Moderate	Very High	Moderate	Satisfactory in Military Service	Extremely Difficult	Good if Tank Not Initially Damaged
Onboard N_2 Generation	Moderate	High	Moderate-High	Not Evaluated	Extremely Difficult	Good if Tank Not Initially Damaged
Foam	High	Not Known	High	Good in Military Service	Extremely Difficult	Good for Intact Tanks
Foil	High	Not Known	High	Not Evaluated	Not Possible	Good for Intact Tanks
Tank Suppresion System	Moderate	Moderate	High	Not Evaluated	Extremely Difficult	Not Evaluated
Vent Flame Arrestor	Low	Low	Low	Good	Yes	Good if Tank Not Initially Damaged

Figure 4: Elimination of Fires Inside Fuel Tanks

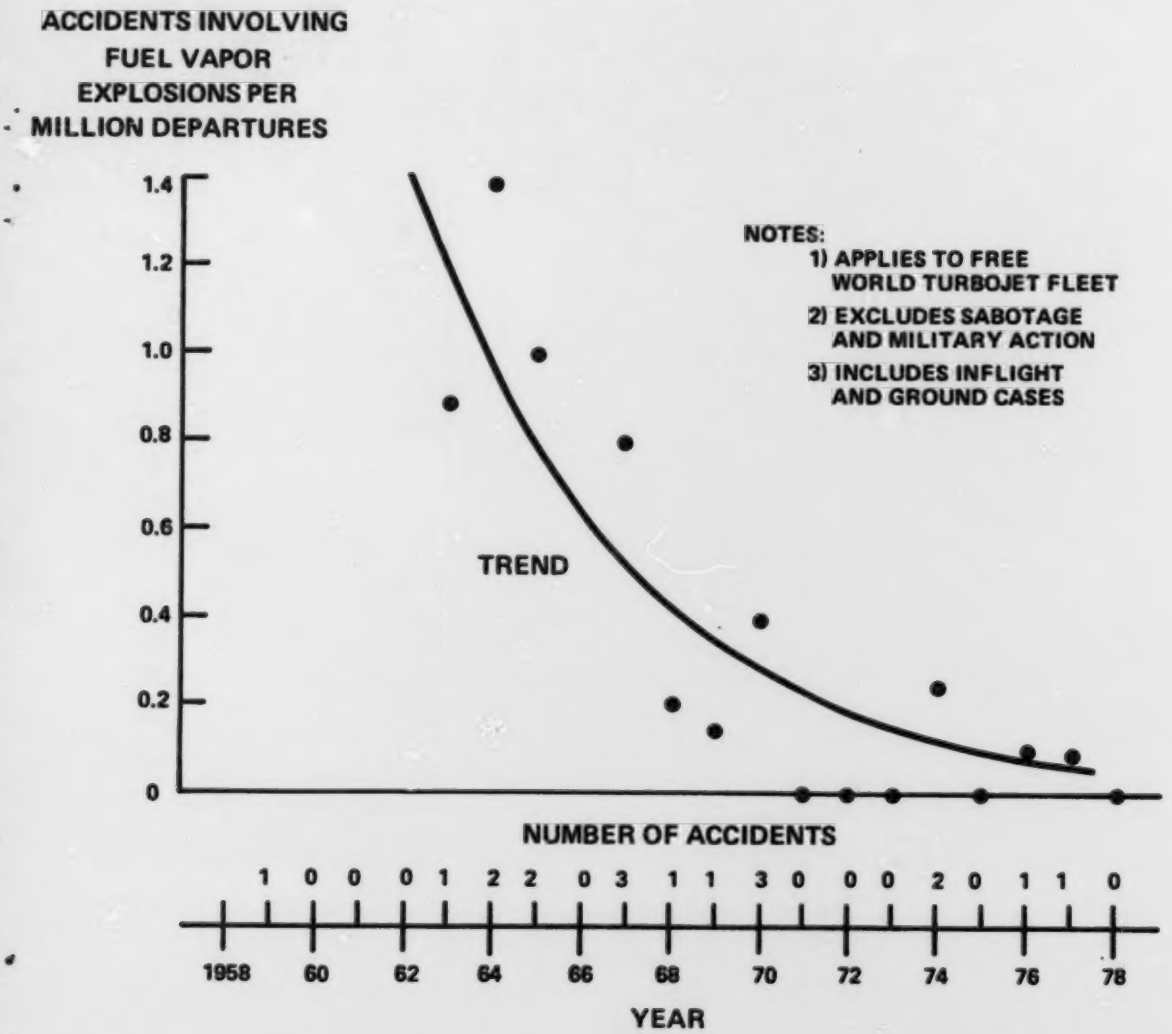
ACCIDENTS INVOLVING FUEL VAPOR EXPLOSIONS PER MILLION DEPARTURES
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
NOTES:
1) APPLIES TO FREE WORLD TURBOJET FLEET
2) EXCLUDES SABOTAGE AND MILITARY ACTION
3) INCLUDES INFLIGHT AND GROUND CASES
TREND
NUMBER OF ACCIDENTS
1 0 0 0 1 2 2 0 3 1 1 3 0 0 0 2 0 1 1 0
1958 60 62 64 66 68 70 72 74 76 78
YEAR

FIGURE 5. TANK EXPLOSION ACCIDENT RATE WORLD WIDE AIR CARRIERS - ALL OPERATORS

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The obvious difference in fuel system and aircraft design and the crash scenario is further complicated by the definition of "impact survivable." The Army bases its determination of whether or not an accident is impact survivable on an assessment of the inertia forces transmitted to the occupant through his seat and restraint system and on whether or not the cabin structure collapsed within the occupant's envelope. On the other hand, the FAA considers a crash survivable if one occupant survives the impact event. Because of the size of transport aircraft and the correspondingly high energy absorbing potential, it is conceivable that some occupants will survive very high crash impact velocities. On the other hand, because of the relatively small size of Army helicopters, all occupants and systems are exposed to approximately the same crash environment facilitating a relatively clean definition of an impact survivable crash.

Transport aircraft fuel tanks fall broadly into two categories - integral wing tanks and fuselage tanks. The application of crashworthy bladder tanks to integral wing tanks cannot be accomplished without a complete redesign of the wing because of its multi-cellular construction. Furthermore, it cannot be said with certainty that crash-resistant fuel tanks would provide fire protection in crash scenarios that include wing separation.

Federal regulations require that damage to the airplane main landing gear system during takeoff and landing shall not cause spillage of enough fuel to constitute a fire hazard. The fuel tank and landing gear support structure is designed to higher strength than the gear to prevent fuel tank rupture due to an accidental landing gear overload. This design requirement is further extended to include structural attachments to the wing fuel tank which might be overloaded during a wheels-up or partial wheels-up landing. Flap hinges and engine mounts, for example, are designed to fail without rupturing the tank.

Before discussing the application of crash-resistant fuel tanks in the fuselage area, something should be said about current fuselage design practices. Fuselage fuel may be carried in the center wing structure or in a pressurized area such as a cargo compartment. Fuel tanks in the center wing structure are designed to meet the "g" loads prescribed for emergency landings.

In airplanes having fuel tanks located within the pressurized area, typically the cargo compartment, particular attention is paid to minimizing the risk of fuel spillage. An example of one such design is shown on Figure 6. The tank is composed of an aluminum honeycomb outer shell with bladder cells inside. The tank is supported from the floor beams in such a manner as to preclude body structure deflections from loading the tank. Clearances from adjacent structure are provided around the tank.

The fuel and vent lines that connect the tanks to the main fuel system incorporate drainable and vented shrouds. These lines are either designed to "break away" from the auxiliary tank or sufficient stretch is provided to accommodate tank movement without causing fuel spillage. Hoses that are required to stretch are subjected to what is normally referred to as the "guillotine test." The hose is pressurized and clamped at both ends to simulate its mounting in the aircraft, then a sharp pointed load is applied in the middle of the hose. The hose must not leak when stretched to its maximum.

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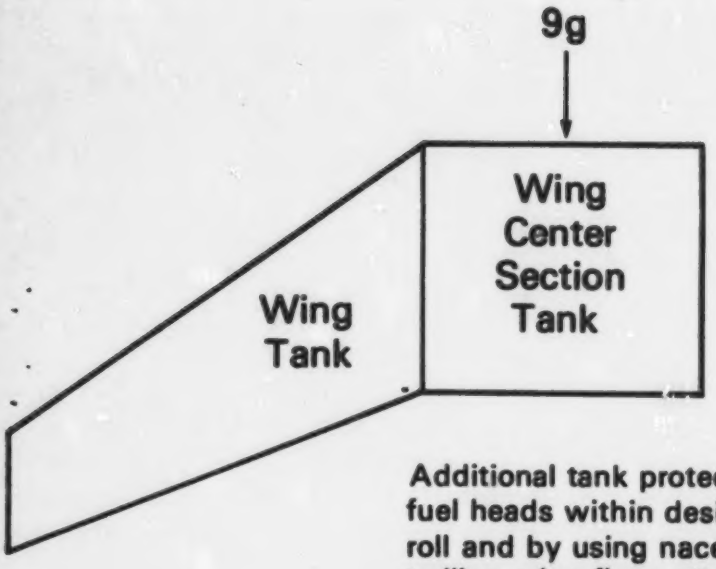
Wing Center Section Designed per FAR 25.561

Forward	9.0g
Downward	4.5g
Upward	2.0g
Sideward	1.5g



Additional tank protection obtained by keeping fuel heads within design limits during 1 radian/sec. roll and by using nacelle strut. Landing gear and trailing edge flaps attachments for controlled breakaway.

Figure 7: Fuel Tank Load Factors

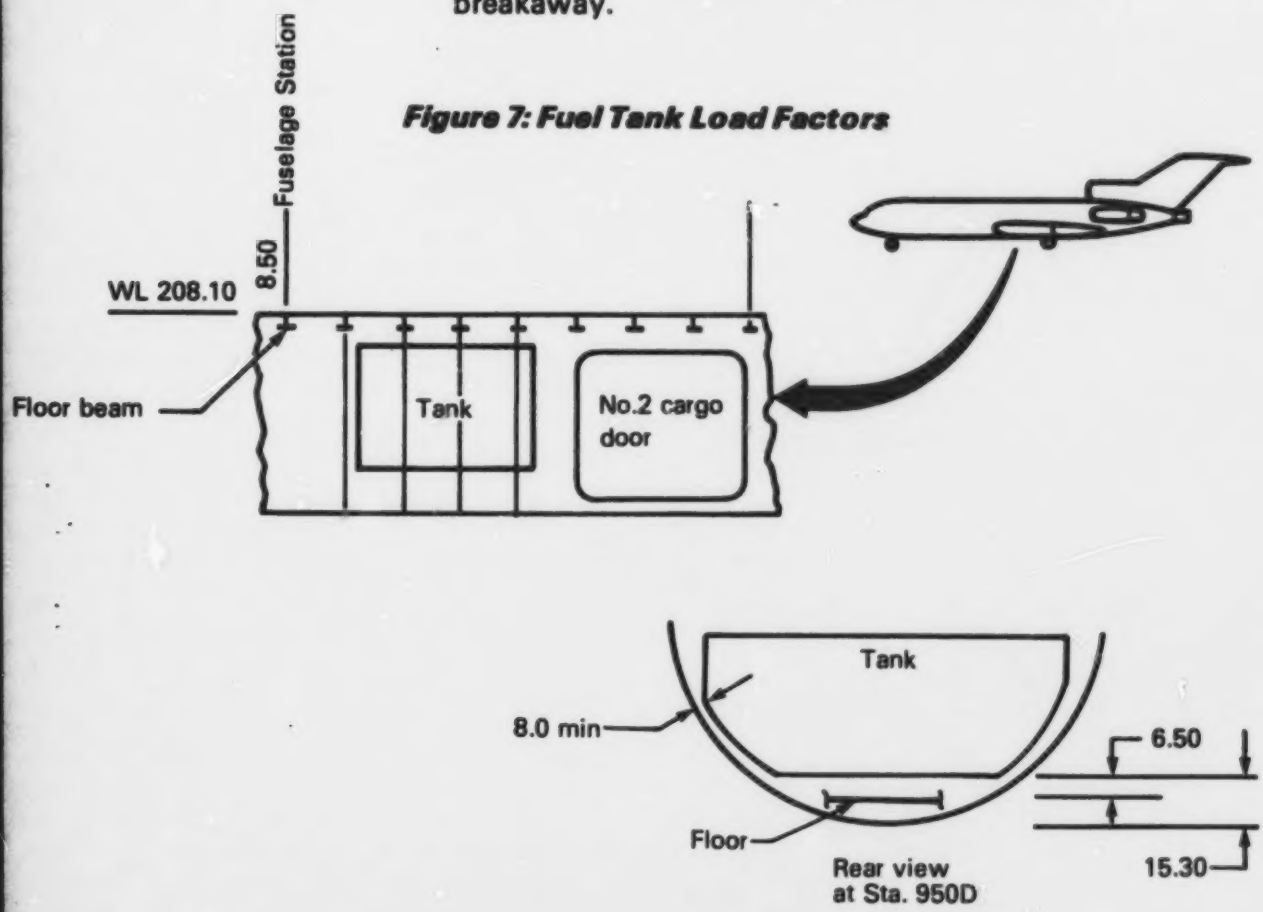


Figure 6: Cargo Compartment Tank Installation

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During the design of the tank installation, prior accident history is reviewed to ensure that likely crash scenarios are considered and that possible leakage of fuel is minimized. For example, accidents or incidents where the gear has separated are reviewed to insure that the tank will not be hit by a displaced gear. Also, incidents or accidents where the fuselage has been crushed are reviewed to insure that there is adequate clearance between the fuselage and the fuel tank. In addition, incidents or accidents where the fuselage has broken fuselage has broken are reviewed to ensure that the auxiliary tank is not located where such breaks typically occur.

In summary, it can be said that the fuselage fuel tank design:

- o Exceeds FAR requirements
- o Is more rugged than center section tanks
- o Provides considerable clearance
- o Allows tank displacement without fuel line breakage.
- o Location results in minimal spillage exposure.

Crash-resistant fuel tank (CRT) installations in wing and fuselage areas were evaluated. A summary of the results of this evaluation is shown in Figure 7. As anticipated, the wing installation shows excessively high penalties in almost every category evaluated. On the other hand, the fuselage installation results in only low to moderate penalties.

One other source of potential fuel spillage is a broken engine fuel supply line when nacelle damage occurs. An existing regulation, FAR 25.1189, requires that, "Each tank-to-engine shut-off valve must be located so that the operation of the valve not be affected by powerplant or engine mount structural failure." However, in one incident where a nacelle separation from the wing in flight could not be detected by visual means, the crew interpreted the instrument indications as an engine flameout. Since normal shutdown procedures only required that the engine fuel shutoff valve be closed, the tank-to-engine shutoff valve was not actuated. Consequently, excessive fuel spillage occurred after the aircraft came to rest resulting in a fire. Subsequently, the fuel system design was modified to include closure of this valve during normal shutdown. Incorporation of this feature or its equivalent in the fuel system design is shown in Figure 7, to have minimal impact on the airplane design and operation. The results of this brief evaluation indicate that a careful analysis of crash data history to explore modes of failure is essential to determine if improvement of fuel retention during transport airport crashes can be achieved. A research program involving the 3 domestic widebody airframe manufacturers was initiated in January 1980 for the purpose of developing crash scenarios and recommending a future test and analysis effort for the development of improved crashworthiness.

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Summary Evaluation of Concepts

Concept	Weight	Volume	Cost	Reliability	Retrofit	Effectiveness
CRT in Fuselage	Moderate	Low	Low	Passive	Feasible	Not vs All Possibilities
CRT in Wing	High	High	High	Passive	Difficult	Not vs. All Possibilities
Emergency Fuel Shut-off	Low	Low	Low	Good	Yes	Good

Figure 7: Fuel Containment

From the foregoing, it was concluded:

- o It is feasible to install crash-resistant fuel cells in fuselage cargo compartments.
- o It is not feasible, in most conventional transport aircraft, to install all the wing fuel in crash-resistant fuel cells.
- o It may be feasible to install some degree of crash-resistance including break away fittings at critical locations in some state-of-the-art aircraft wings, depending upon specific type design.
- o The existing Federal Aviation Regulations allow the use of crash-resistant fuel cells in transport aircraft.
- o Further definition of criteria should evolve from total aircraft crashworthiness considerations. The research contracts with the three wide-body manufacturers should accomplish this objective.

Anti-Misting Fuels

The fundamental consideration in developing a crash-safe fuel is to produce a fuel which will not burn in a crash environment and which will not compromise engine performance throughout the aircraft operating envelope. Anti- misting kerosene (AMK) is the latest development in the search for such a fuel. An anti-misting additive prevents the fuel from breaking up into a fine, highly combustible mist when subjected to the high shear rate expulsion of fuel from a small tank opening or by air shear breakup of the large fuel masses expelled from damaged tanks during crash decelerations. Eliminating or preventing the rapid development of a large fire around an aircraft involved in an impact survivable accident where fuel tank rupture occurs will allow more time for passenger and crew evacuation and result in a higher rate of survivability in this type of accident.

The anti-misting quality is imparted to the fuel by the addition of low concentrations of shear-sensitive high molecular weight polymers. The additive currently being evaluated by the FAA is a British-developed polymer known as FM-9.
AMK is in the early stages of its development. The current candidate has already demonstrated its ability to minimize, and in most cases eliminate entirely, the fireball frequently experienced when fuel is released during a crash although many factors are yet to be investigated. AMK offers a tremendous potential for post-crash fire hazard reduction. With development, it is expected to have a minimum impact on aircraft operation and maintenance.

Major questions yet to be answered include the effects of the additive on static charge generation and relaxation, engine starting and relight characteristics, heat transfer characteristics, filterability, materials compatability, fuel oxidative stability and storage stability, as well as costs.

The most important property of AMK, its tendency to form large droplets when sheared, is not a desirable characteristic when the fuel reaches the engine combustor. Consequently, development of a degrader to restore the fuel ignitability just prior to entering the engine combustor, is high on the list of development priorities.

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Although no specifications for AMK exists as yet, the following properties have been established as targets:

- o Heat content equivalent to current fuels.
- o Anti-misting quality maintained during handling.
- o Minimum impact on engine start and relight.
- o Acceptable pumpability and flowability.
- o Compatable with existing materials and components.
- o Achievevable at reasonable cost.

In spite of the many questions yet to be answered, the technical community's reaction to AMK is highly favorable at this stage of its development. Its fluidity has been improved significantly without compromising its anti-misting qualities. The development of a suitable degradation process is encouraging. Test programs are continuing in the areas of engine and fuel systems compatibility, air shear and flammability, and rheology definition. In addition, large scale tests are being implemented.

If no unacceptable aspects of AMK develop in the continuing program, it is estimated that it could be introduced for commercial aircraft usage as early as 1984 but at least within 10 years.

Alternate Fuels

The current effort to develop new sources of crude oil such as synjet derived from coal or shale oil must not overlook their post-crash fuel fire hazard potential. Although the type of hydrocarbons may differ among synjet and petroleum Jet A fuels, these differences will not influence the probability or nature of fire in a crash situation if the fuels are produced to the same specification. The effect of broadened fuel properties and alternate fuels with completely different properties on fuel safety is discussed briefly in the following paragraphs.

One alternative fuel being studied has a flash point specification 10° F to 20° F lower than the current commercial Jet A or Jet A-1 specification of 100° F minimum. The incentive for considering such a jet fuel is increased potential availability and more refinery flexibility in meeting other critical jet fuel quality requirements such as freezing point. The Canadian and Russian commercial jet fuel specifications (CAN 2-3.23-77 and GOST 10227, respectively) have 33° C (92° F) and 28° C (82° F) minimum flash point requirements. The recent reduction in flash point was adopted by the Canadians because trends showed a reduced growth rate for gasoline and a healthy growth for distillates including jet fuel. Considering ambient temperatures in Canada, laboratory data, and other operational factors, it was concluded that the reduced flash point would have a minimal effect on fire safety (Reference 16).

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Although it is recognized that fuel types currently being studied will have a minor effect on the overall safety of turbine aircraft, it is known that large differences in flash point can influence fire safety. Consequently, decreases in flash point to increase jet fuel availability must be carefully considered before a decision is made.

On the basis of laboratory data and its relationship to the accident record, a fuel with a flash point of 80-90° F would be expected to behave more like Jet A (100° F flash point) in crashes and inflight fires according to Reference 3. Any difference in fire safety compared to Jet A would be expected to occur when the fuel temperature is at or near the flash point. It is recommended that FAA sponsor studies to quantify what effect reduced flash point fuels might have on aircraft fire safety in the U.S.A.

Liquid hydrogen and liquid methane are being considered as aircraft fuels. The use of cryogenic fuels involves the hazards arising from low temperatures as well as those of combustibles. Studies of safety problems that might arise from airline use of these cryogenic fuels should continue and keep pace with the overall aircraft development studies.

Conclusions

Any evaluation of systems for reducing the fuel fire hazard in impact survivable accidents must consider the effects of the system in all phases of the aircraft operation: on the ground, in-flight and at landing and takeoff. The tendency to consider the merits of the system in the impact survivable environment only can lead to erroneous conclusions which, if implemented, could be to the detriment of the traveling public. Consequently, the conclusions reached in this section may differ in some respects from those expected for the crash situation only.

The primary conclusion reached in evaluating both existing and proposed fire hazard reduction systems in that the use of anti-misting fuels has the greatest potential for improved safety by essentially eliminating the development of fuel fires in a post-crash environment. While much further development work needs to be done to improve the currently promising anti-misting fuels for practical use in fuel systems, the research on such fuels should be expedited.

The improvements introduced into existing designs in recent years which meet or exceed Federal Aviation Regulations have proven to be effective. The proposed more complex systems do not appear to offer significant additional protections in their present states of development. Furthermore, these more complex systems have an appreciable weight, complexity, and maintainability penalty which will degrade overall airplane performance and safety.

Fuel tank inerting may have a potential for future aircraft safety improvements only if its weight and complexity can be significantly reduced through further development.

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VI

R & D CONSIDERATIONS

Summary and Perspective

Although there have been a recurrent number of in-flight fire incidents, all fatalities attributable to fire in U.S. air carriers have occurred in crash accidents. Therefore, it is imperative that research and development be conducted in the context of a postcrash fire. A postcrash cabin fire scenario is described in this chapter. This scenario has been utilized and analyzed in the FAA C-133 full-scale fire test facility. The fire scenario was conceived to provide a realistic postcrash fire wherein the ignition and burning of interior materials would become a significant factor affecting the survivability of cabin occupants. Placement of the scenario within the spectrum of actual postcrash accidents will be an important task of the comprehensive FAA/NASA sponsored study by Boeing, Lockheed, and McDonnel-Douglas of past transport accidents.

Aircraft cabin materials fire safety technology has historically been focused on polymeric material development. Most of these materials, which are functional, comfortable, decorative, and economical, will burn under certain conditions. Past research has emphasized modifying these materials or developing alternative materials to reduce (but not necessarily eliminate) burning and the evolution of smoke and toxic gases. We are able to test these materials in the laboratory and provide relative data on burning (e.g., flame spread, heat release rate), and smoke evolution. The problem; however, is to relate such data to behavior in an aircraft fire and to assess its relationship to survivability in a post-crash fire in the design of aircraft.
It is simplistic to demand a continual change to materials that burn less readily or give off less smoke or toxic gas. Before there is a requirement for such changes, it should be possible to define, even approximately, the increase in survivability that would accrue. To do so one should be able to predict (analytically or empirically) the course of a fire in a real aircraft containing a mix of materials. The goal is to predict the additional escape time provided by improved materials.

The leading organizations engaged in research and testing related to aircraft cabin fire safety are the FAA, NASA, and the three major airframe manufacturers (Boeing, Lockheed, and McDonnel-Douglas). Areas of responsibility between FAA and NASA are defined in a memorandum of understanding (MOU) Reference 21. Industry efforts have been supported by NASA as part of the past FIREMEN program or by internal funding as part of the IRAD (Independent Research and Development) program.

The FAA program is described in detail in a recently published program plan document Reference 21. A 3-year time framework is described for the comprehensive development of test methods and criteria for cabin materials. A longer range 6-year program has been prepared by NASA at JPL which focuses on

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the development of a mathematical cabin fire model. Of a shorter time period than either the FAA or NASA programs is an 18-month program prepared by Boeing to correlate full-scale and laboratory testing, culminating in an interim test methodology for cabin materials. The FAA program plan was endorsed by the SAFER Committee after the program was presented to the committee on March. However, the NASA modeling plan and Boeing interim proposal must be integrated into the FAA program plan.

Prediction of Cabin Materials and Human Response to Fire Modeling

The ability to analytically or empirically describe a fire and its progress is desirable for designing interior systems and selecting materials, and relating small and full scale test data to materials performance in an accident. Fire modeling in government and industry is currently in the early stages of development and offers many advantages in cost and time savings. A concerted effort should be made to accelerate the empirical correlation of laboratory and full scale tests and to advance analytical modeling development.

Analytical modeling is seen as a long-term effort in cabin fire safety technology. The SAFER R&D Subgroup expended extensive effort in developing both short term and long term descriptions of modeling needs which are attached in Volume II. Modeling would intelligently predict cabin materials behavior for given fire scenarios and the resulting human survivability envelope, given the establishment of standards for human tolerance limits. Each of these elements is now discussed.

Aircraft Cabin Fire Scenario

General

In response to a SAFER Recommendation, the FAA developed the following typical scenario. A wide body jet transport with a 57 percent passenger load factor crashed on the runway of a major airport following an abnormally high descent rate. The accident occurred on a sunny afternoon. This scenario will be refined, and perhaps other scenarios added, following analysis of NTSB accident reports and data relating to actual
crash conditions. This activity is currently underway by the three major airframe manufacturers under terms of NASA and FAA contract studies for improving structural integrity.

Fire Description

During the crash deceleration an integral tank in the right wing was penetrated by debris, spilling fuel which was immediately ignited by frictional sparking. A train of burning fuel was observed behind the decelerating airplane. As the airplane came to rest a large external fuel fire erupted immediately in the vicinity of a fuselage rupture. Except for this opening in the fuselage on the right side, the fuselage was otherwise intact. The size of the opening approximates a rectangle 76 inches high and 42 inches wide. The two forward doors on each side of the fuselage were jammed and passengers and crewmembers - none of whom were immobilized or traumatized - utilized the remaining six doors to evacuate the airplane. During the crash deceleration, the main and nose landing gears were sheared off and the airplane eventually came to rest on its

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belly in a level orientation. All emergency lighting systems operated properly. (Note: Based on past accident analyses, other plausible openings for the entry of fire are inadvertently opened doors or small ruptures beneath the cabin floor line.) Other door openings were not subjected to the pool fire, which involved several thousand gallons of fuel. The pool fire reached heights of approximately 75 feet, extended beneath the belly of the fuselage and completely covered the rupture. The pool fire flames were attached to the fuselage. Only those cabin materials very close to the rupture opening were subjectd to the intense heat and flames generated by the fuel fire. A relatively steady 3 mph wind was blowing in a direction perpendicular to and toward the fuselage. The pool fire was upwind of the fuselage. The radiative heat flux in the fire may have reached 14 BTU/ft^2-sec and at the center of the cabin opposite the rupture the flux would have been at least 1.8 BTU/ft^2-sec. There was moderate penetration of flames from the fuel fire primarily in the vicinity of the ceiling next to the opening.

Evacuation Description

At the first indication of fire at the ruptured fuselage location, those passengers nearby immdiately began moving away from the fire.

Surviving passengers and crew utilized one-half of all the exits to evacuate the airplane. Estimates for the evacuation time ranged from 90 seconds to 3 minutes. The shell of the fuselage remained primarily intact during the evacuation although the cabin was eventually gutted.

Design Fire Considerations

An important feature of an aircraft postcrash cabin fire is the possibility of intense thermal radiation from a large external fuel fire through a fuselage opening.

In order to be representative of the large fuel fires characteristic of many aircraft accidents, a design fire should be "optically thick" to produce this intense radiation.
The severity of the fire exposure to interior materials increases with the degree of flame penetration.
Cabin hazards arising from the fuel fire are dependent on the amount of flame penetration into the cabin. The degree of flame penetration for the design fire must be selected to provide cabin hazard levels well within human survival limits over a prescribed time interval.

Human Tolerance Limits

Limited information is now available on the limits of human tolerance to heat, smoke, and some toxic gases; however, more work is needed in defining the effects of irritant gases and a definition of human tolerance from a systems point of view. The combined effects of heat, visual disorientation, and the presence of irritating or toxic gases on the behavior of passengers need to be evaluated relative to cabin egress design. Efforts along the line of the FAA Combined Hazard Index (CHI) program are needed. (CHI would account for the combined affects of heat, smoke and toxicity.)

Egress, Lighting, Emergency Communications

These items do not fall under the scope of SAFER; however, the design and development of technology must be done within an overall systems approach for evaluating survivability. Volume II-B contains some commentary on Egress lighting and emergency communication factors, even though the Committee did not discuss them in any detail, nor formulate any related recommendations.

Fuselage Fire Resistance

Whether the fuselage is a wide body type or a standard body type will have a crucial bearing on the development of the fire and its hazards. For example, compared to a standard body jet, a wide body jet is more resistant to burn through by an external fuel fire, furnished with more flame retardant cabin materials, and encompasses a large cabin volume with possibly greater dilution of combustion products.

Modeling

In order to intelligently predict human survivability, there is a need to relate material laboratory test results with aircraft cabin geometry, a fire scenario, and human tolerance limits. It is necessary to have analytical or empirical tools to model the fire. There are two aspects to this issue which are complementary and integrated activities. They are:

1. Short term analytical and empirical methods to correlate full scale, model, and laboratory testing.

2. Long term development of mathematical tools to predict the progress of burning, temperature, and gas species distributions in a defined geometry.

These two aspects should not be considered as competitive activities; but rather both part of a continuum of activities from which increasingly valuable modeling tools emerge.

Short-Term Plan

The base for the development of such a methodology has been laid down with several programs including the FAA contract with McDonnell-Douglas for the "Combined Hazard Index" (CHI), Boeing fire test methodology program started in 1974 and the NASA-JSC contract on fire test methods which Boeing completed in October 1978. There are probably others, but these are notable because they developed within two of the three major airframe companies exceptional knowledge pertaining to the problems of material evaluation and fire threat definition. This background combined with the knowledge of airplane construction and parts fabrication provides a currently unique capability to develop a methodology to evaluate the fire performance of materials in a fashion both effective in materials control and practical in application.

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At the request of the SAFER R&D Subgroup, the program outlined on Figure 8 was proposed by Boeing to develop this capability in the shortest time possible. The correlation study in the proposal is similar in many respects to the FAA-sponsored CHI contract scheduled for completion in December 1980. Major similarities include the utilization of the OSU chamber for the measurement of rates of emissions of heat, smoke, and toxic gases, and large-scale tests on single materials as part of the test methodology development. Therefore, many of the provisions of the correlation study are contained in the CHI study. It is recommended that the CHI contractor, McDonnel-Douglas, be requested to make a detailed presentation to a select group of FAA, NASA, and industry on the design, development, validation, and limitations of the CHI test methodology. In light of the degree of success of the CHI methodology, the FAA should request Boeing to redefine and describe in detail the elements of their empirical correlation study. At that point in time, the FAA should be in a better position, taking into consideration suitable inputs and recommendations by NASA and industry, to consider the revised Boeing proposal.

Much of the work required in Phases II-V of the proposed plan has already been started during the previously noted programs. The main ingredients for the success of such a short term program are: (1) a sense of urgency to resolve the material evaluation problem within the state-of-the-art, (2) recognition that in this case only the airframe companies have the test correlation, airplane design, material selection and laboratory test application background to develop the practical solution in a timely fashion, (3) a means of formally requesting and obtaining the participation of the industry in the effort, and (4) timely testing and analysis support by the NASA and FAA-CAMI, and effective testing and program administration support by the FAA-TC.

Long Term Modeling Plan

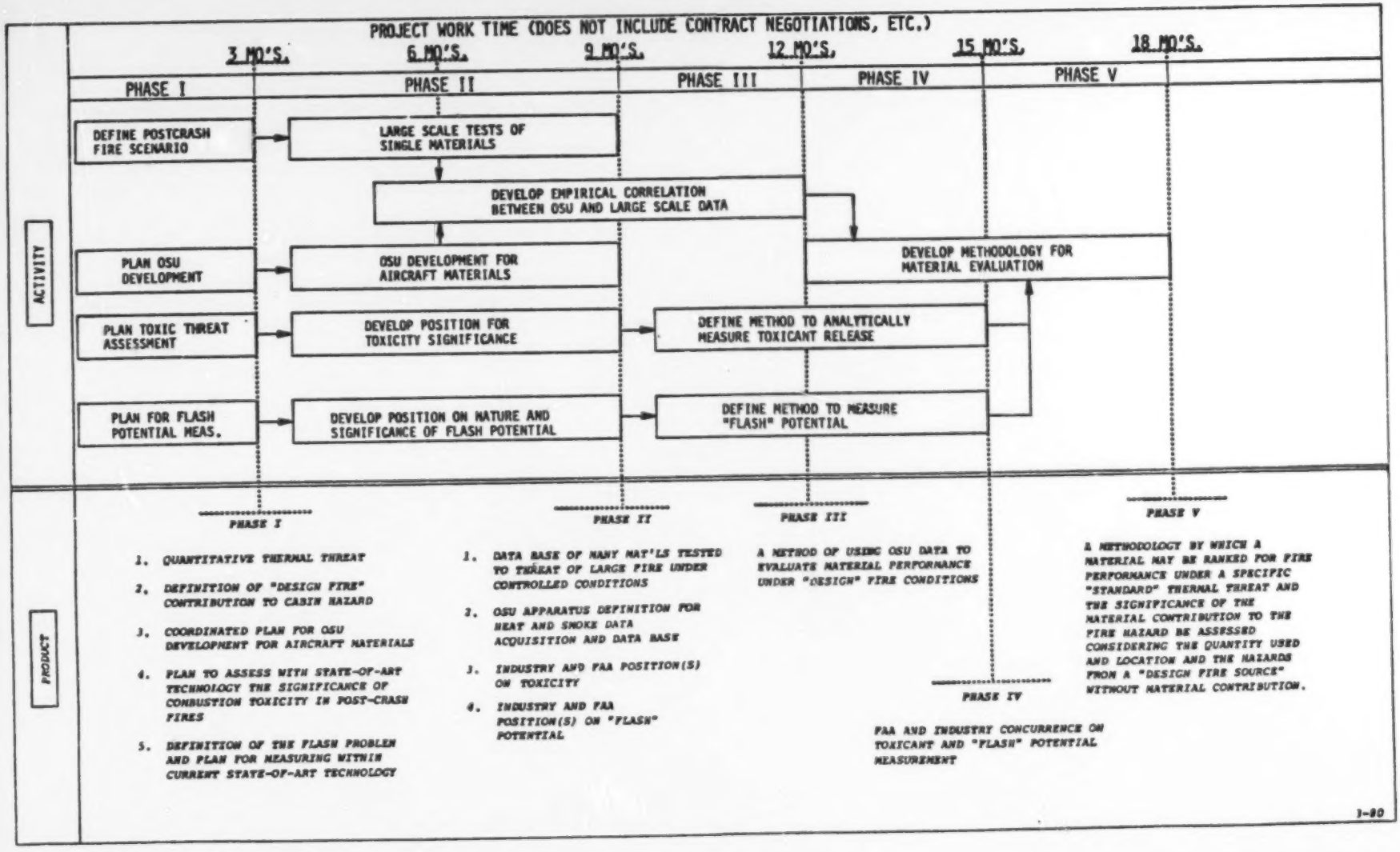
General

The SAFER R&D Subgroup requested that NASA's Jet Propulsion Laboratory (JPL) develop a comprehensive long-term aircraft fire modeling technology plan. It is included in Volume II. The plan was designed to provide analytical models which possess well-defined predictive capabilities with particular emphasis on user needs. Furthermore, since analytical methods should be developed in conjunction with related experiments, the long-term plan also includes test programs which are necessary to establish an effective and valid predictive technique.

Preparation of the plan began in October 1979 and inputs were made by the airframe manufacturers, Federal Aviation Administration, National Bureau of Standards and the National Aeronautics and Space Administration. Phase I, Definition of Fire Modeling Technology Requirements, of the 6-phase plan has been substantially completed by NASA JPL and the phase 1 results are also included in Volume II.

The overall objective of this Fire Modeling Technology Plan is to develop analytical and experimental methods for use in aircraft design and testing to reduce the post-crash fire hazard. Specific objectives developed in response to previously discussed needs are:

FIGURE 8


PROJECT WORK TIME (DOES NOT INCLUDE CONTRACT NEGOTIATIONS, ETC.)
3 MO'S.
6 MO'S.
9 MO'S.
12 MO'S.
15 MO'S.
18 MO'S.
PHASE I
PHASE II
PHASE III
PHASE IV
PHASE V
ACTIVITY
DEFINE POSTCRASH FIRE SCENARIO
LARGE SCALE TESTS OF SINGLE MATERIALS
DEVELOP EMPIRICAL CORRELATION BETWEEN OSU AND LARGE SCALE DATA
PLAN OSU DEVELOPMENT
OSU DEVELOPMENT FOR AIRCRAFT MATERIALS
DEVELOP METHODOLOGY FOR MATERIAL EVALUATION
PLAN TOXIC THREAT ASSESSMENT
DEVELOP POSITION FOR TOXICITY SIGNIFICANCE
DEFINE METHOD TO ANALYTICALLY MEASURE TOXICANT RELEASE
PLAN FOR FLASH POTENTIAL MEAS.
DEVELOP POSITION ON NATURE AND SIGNIFICANCE OF FLASH POTENTIAL
DEFINE METHOD TO MEASURE "FLASH" POTENTIAL
PRODUCT
PHASE I
1. QUANTITATIVE THERMAL THREAT
2. DEFINITION OF "DESIGN FIRE" CONTRIBUTION TO CABIN HAZARD
3. COORDINATED PLAN FOR OSU DEVELOPMENT FOR AIRCRAFT MATERIALS
4. PLAN TO ASSESS WITH STATE-OF-ART TECHNOLOGY THE SIGNIFICANCE OF COMBUSTION TOXICITY IN POST-CRASH FIRES
5. DEFINITION OF THE FLASH PROBLEM AND PLAN FOR MEASURING WITHIN CURRENT STATE-OF-ART TECHNOLOGY
PHASE II
1. DATA BASE OF MANY MAT'LS TESTED TO THREAT OF LARGE FIRE UNDER CONTROLLED CONDITIONS
2. OSU APPARATUS DEFINITION FOR HEAT AND SMOKE DATA ACQUISITION AND DATA BASE
3. INDUSTRY AND FAA POSITION(S) ON TOXICITY
4. INDUSTRY AND FAA POSITION(S) ON "FLASH" POTENTIAL
PHASE III
A METHOD OF USING OSU DATA TO EVALUATE MATERIAL PERFORMANCE UNDER "DESIGN" FIRE CONDITIONS
PHASE IV
FAA AND INDUSTRY CONCURRENCE ON TOXICANT AND "FLASH" POTENTIAL MEASUREMENT
PHASE V
A METHODOLOGY BY WHICH A MATERIAL MAY BE RANKED FOR FIRE PERFORMANCE UNDER A SPECIFIC "STANDARD" THERMAL THREAT AND THE SIGNIFICANCE OF THE MATERIAL CONTRIBUTION TO THE FIRE HAZARD BE ASSESSED CONSIDERING THE QUANTITY USED AND LOCATION AND THE HAZARDS FROM A "DESIGN FIRE SOURCE" WITHOUT MATERIAL CONTRIBUTION.
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1. Determine the capabilities of existing modeling methodologies relative to user needs; and accelerate activities to improve these methodologies with regard to the stated needs.

2. Develop a detailed, analytical fire dynamics model that will describe the post-crash scenario; and develop other new modeling methodologies as required.

3. Determine the capabilities of existing small- and large-scale test methods for model application.

4. Develop and refine appropriate test methodologies which can be used with models to give well defined predictive capabilities.

5. Develop hazard evaluation modeling methodologies.

For a number of years, the FAA has sponsored the development of a mathematical cabin fire model at the University of Dayton Research Institute (UDRI). Of necessity, development of the UDRI model must fit within the 3-year time framework of the FAA program plan. The FAA has identified "weak" portions of the UDRI model which require improvement. While SAFER has endorsed a long-range mathematical modeling endeavor, it is recommended that the long-range program be structured to provide "early" products (subroutines) to upgrade the UDRI model. These "early" products include theoretical modeling of burning processes of aircraft mmaterials and of flame spread under superimposed radiation and ventilation, including scale and ventilation effects.
During the entire Fire Modeling Technology program there should be close coupling and interactions between the activities associated with modeling, hazard evaluation, experimental/testing and existing aircraft design and design methods. The establishment of a government-industry Technical Working Group is intended to assist in furthering these interactions.

Finally, the long-term plan would be complimentary to the short-range plan for the development of empirical correlation methods.

Testing

General

Testing methodology was singled out as a technology requirement because of the lack of reliable predictive methods which are demonstrated to be correlated with performance in an accident. Near term focus should be on well instrumented full scale tests (e.g., FAA's C-133 tests and NASA's B-737 tests) to provide quantitative design requirements, contribu- tion of cabin interior materials to the post-crash fire hazard, and to realistically evaluate current and new materials systems. Mockup tests, similar to the concepts used in the McDonnell-Douglas Cabin Fire Simulator, should be employed to provide similar evaluations in the future at lower cost. Also, further development is needed to develop correlation between lab tests and full scale/accident performance. The SAFER R&D subgroup made the following findings and recommendations.

Findings.

1. Full-scale and mockup testing are required because there is a lack of reliable predictive methods.

2. Laboratory and full-scale test correlation with accident performance needs extensive development.

3. Correlation of laboratory tests with full-scale tests requires further effort.

4. The Ohio State University (OSU) Heat Release calorimeter methodology appears to provide the most promise for long-term laboratory test application. The OSU shows promise of providing correlation with additional work. Laboratory methods for measuring toxic gases do not currently correlate with full-scale test results and require further work. Part of this effor should be conducted as an ASTM activity after the tests are proven to be valid indicators for at least ranking the various materials regarding their relative hazards.

Recommendations.

1. Continue full-scale tests with the C-133 at the FAA Technical Center and B-737 at NASA, Houston test articles. These tests should utilize an agreed upon fire scenario and be completed in approximately 2 years. Additionally, the test program should include advanced material tests after testing of contemporary materials is completed. (Note: It is recommended that for technology development purposes, a 5-minute evacuation time be considered to represent the majority of cases.)

2. Mockup test configurations should be defined and the validity verified. This type of test is less expensive to conduct and provides more rapid turn-around times.

3. Further effort should be expended to correlate laboratory tests with full-scale and mockup tests.

4. Expedite the development of the OSU Chamber Calorimeter and evaluate its use as a regulatory tool (within 3 years). Establishment of an industry/government test development advisory committee is essential.

Coordination of R&D Between Domestic and International Groups

An important lesson learned during the SAFER proceedings is the strong desire by industry to establish a government-industry forum for exchanging technical information, coordinating research and technology planning and the development of materials and safety fuel standards. The R&D subgroup after exploring several alternatives, recommended that such activities be pursued by the ASTM Committee F-7, Aerospace Industry Methods (Cabin Interior Materials) and ASTM Committee D-2, Petroleum Products and Lubricants (Modified Fuels).

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The FAA in its response to the interim SAFER Recommendations briefed SAFER on April 5 on two draft parallel research and development plans designed to improve human survivability and reduce hull losses resulting from fires in otherwise crash survivable accidents. Both plans will develop the technical data base by 1984 which when coupled with other rationale, i.e., economic analyses, will support FAA regulatory proposals. The Cabin Fire Safety Plan will evaluate current and improved cabin interior materials, determine means to retard the progress of cabin fires, improve evacuation systems, and improve crash-fire-rescue effectiveness.

The Anti-Misting Kerosene (AMK) Plan will determine AMK feasibility, develop promising AMK additives, demonstrate AMK effectiveness in large and full scale tests, and develop recommendations for the use of AMK in civil aviation operations.

The draft program plans have subsequently been developed to a final form.

The SAFER Committee has reviewed the Cabin Fire Safety, FAA-ED-18-7, and Anti-Misting Kerosene, FAA-ED-18-4, Program Plans and recommends that the FAA vigorously pursue them in parallel until such data are available to determine if continued parallel research is required.

Complementary to the SAFER activity, the FAA, NTSB, and the aviation community are expanding the scope of accident investigations to fully develop the performance of cabin interior materials, fuels, and aircraft seats and airframe structures. In certain of these investigations experts from NASA will be involved.

At the time this report was prepared, NASA was developing long-term plans for fireworthiness materials, modeling and safety fuels research. The planning includes specific research at each NASA Center (Ames, JPL, Johnson, and Lewis) based on technical expertise and facilities and uses draft FAA-TC Engineering and Development Program Plans for Cabin Fire Safety and Anti-Misting Kerosene in the 1981-1984 time frame as inputs for short-term requirements. The joint research is conducted under terms of a formal NASA-FAA agreement established during the Firemen Program. NASA and FAA are also establishing the details of coordinated research for improving transport aircraft structural integrity that would enhance crash survivability.

International research coordination and cooperation is also required because of the potential for implementing more stringent airworthiness requirements for existing and future U.S. manufactured aircraft and the extent of the international accident statistics. The current trend in Europe is for adopting common airworthiness requirements in the form of Joint Airworthness Requirements (JARs) which are heavily influenced by the FAA airworthiness regulations. The FAA and UK-CAA meet annually to review operations and research activities and perhaps this mechanism would serve as a means to enhance international coordination of research and a more extensive, unified approach to fire safety improvement world-wide.

Anti-Misting Kerosene (AMK) Research

AMK has been previously discussed under Fuel System Fire Hazards and at this point, AMK R&D and economics analysis requirements are discussed. NASA and FAA have been conducting AMK research using a British industry developed proprietary additive. Cooperative research between the FAA, NASA and the UK-CAA is conducted under terms of a government-to-government agreement. The AMK additive in jet fuel reduces the possibility of fuel pool fires in crash survival accidents because of the inhibition of the fine fuel mist which typically allows fire-propagation from an ignition source to the fuel pool. SAFER was briefed on the status of US/UK AMK research and the FAA's Program Plan for continued research assuming sufficient rationale will be developed by October-November 1980 for further research. SAFER concurs with the need for further research to include alternate fuel additives to jet fuel and expansion to other fuels that could appear in the market place and where warranted for other aircraft classes, e.g., commuters, corporate, general aviation. Sufficient concurrent research in both research areas, i.e., fireworthy materials and AMK will be required to determine their relative effectiveness and the costs and benefits to the various potential users.

The FAA is faced with multiple research tasks, limited available research funds and pressures to resolve other high priority safety issues. Therefore, it would be reasonable to expect more sophisticated and timely FAA management techniques to determine the extent to which multiple solutions to safety problems should be pursued.

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VII

CREW PROTECTION AND PASSENGER EVACUATION

The scope and expertise of the SAFER Advisory Committee was limited to transport category aircraft and the design aspects of such aircraft as they relate to fire and explosion reduction. Because of the relatively short time involved for the Committee's efforts, attention was focused primarily on impact survivable accidents where control of fire and explosions would enhance occupant survival. Certain of the discussions of the Committee were beyond this scope; however, since they did affect occupant survivability they are reflected here so they can be kept in view for regulatory activities outside SAFER. (See Volume II-B for additional items in this category.) Protection and evacuation of aircraft occupants are the critical elements of safety in a postcrash fire environment. The FAA should work to attain these goals by (1) ensuring that effective escape mechanisms are built into the airframe and are present in the cabin interior, (2) ensuring that the flight and cabin crewmembers are properly trained, protected, and able to direct and assist evacuation, and (3) improving passenger education efforts. In addition, the Committee suggests evaluation of several measures to reduce the hazards present during an inflight fire. It should be noted that these issues, since they were beyond the scope and expertise of SAFER, were not discussed or evaluated by SAFER or its technical groups.

Countermeasures for Inflight Fire Injury

A. Lower Lobe Galley and Lavatory Fire Detectors

Continuing attention to smoke/fire detectors in critical areas such as lower lobe galleys and lavatories is needed.

Consideration should be given to being independently powered with a "press to test" feature for operability and activation indicated by an aural alarm and lights visible to flight attendants. In similar systems now used, very few false alarms have been reported, while several fires have been detected at an early stage.

The lavatories are particularly vulnerable to fires because of:

1. the inability of cabin crew to monitor all passenger uses of the lavatory;

2. the design of the lavatory to provide forced air ventilation for odor prevention which could promote fire propagation;

3. the private nature of the lavatory even when unoccupied. With the door closed, there is little indication of fire to outside observers. In recent tests, two minutes had passed before even wisps of smoke were visible. By then a fire is hard to contain with onboard portable extinguishers.

After a warning, a means to combat an existing fire in a lavatory without opening the door should be developed (NTSB Recommendation).

Lower lobe galleys should have detectors with warning systems that activate in the lower galley as well as the main deck service center since there are times on the ground and in flight when the lower galley is not occupied by a crewmember. An alternative is designing for fire containment, as discussed earlier in this report.

Countermeasures for Postcrash Fire Injury

A. Aircraft Structure

Based upon presentations made to the SAFER Committee and its technical groups, but not discussed or evaluated in detail, the following areas relating to the structure of the transport aircraft may be worthwhile for research, evaluation outside the SAFER Committee:

1. Emergency Exits
   The design of aircraft exits should consider outside visibility as well as the ability to close off an exit inadvertently opened.

   a. Design aircraft door windows to provide flight attendants with sufficient visibility downward and outward to assess conditions on the ground. ("Assessment of evacuation condition," is the flight attendants first step in an evacuation.)
   b. Examples of alternate aids which should be considered are heat sensors or fiberoptic viewing devices which could be placed at exits.

   c. Once a door has been opened inadvertently due to lack of vision of the ground or a noncrew member opening an exit, there should be a means of closing the exit/opening to preclude venting of fire, heat and fumes into the cabin.

   Narrow-bodied aircraft doors have closing capability since they are manually operated. However, on wide-bodied aircraft the emergency door opening mode is pneumatic (DC-10, 747) or spring-powered (1011). Once the door handle is actuated in the emergency mode the door is opened and may not be closed in all cases. This is a factor which must be considered in protecting occupants from intrusion of flames from exterior fires.

B. Aircraft Interiors

Based upon presentations to the SAFER Committee and review by some members of design proposals being discussed in the industry, (but not discussed or evaluated in detail by SAFER or its Technical Groups) the following modifications or studies involving aircraft interiors should be evaluated beyond the SAFER Committee considerations:

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1. Distribution of Emergency Lights

Accident experience has shown that overhead emergency lights currently installed in cabin ceilings and over exits often become obsecured by smoke from burning fuel and aircraft components. This not only prevents rapid visual location of exits by passengers but also eliminates the light source necessary for illuminating an aircraft interior. In view of the potential for obscutation, additional emergency lighting placed at or below armrest level should be considered to provide emergency evacuation guidance and illumination in the relatively clear air found at lower cabin levels.

2. Firehardening of the upper cabin

In addition to the hazard of smoke obscuration heated air also collects in the upper cabin. This stratification of smoke and heat means that the upper cabin can be rapidly subjected to high heat. While passengers and crewmembers have avoided the hazards of smoke and excessive heat by bending low or crawling when exiting the cabin, their egress and survival may be impeded by the effect of the heat on upper cabin materials and equipment. Tests and accident experience have demonstrated that ceiling panels sometims begin to deterioriate structurally while the lower level of the cabin may still be livable. Should deterioration of overhead panels occur, it can represent an impediment to successful evacuation and a source of injury. Further, equipment which is used to aid egress, such as lighting and public address systems, can be disabled by excessive heat. Electrical wiring in overhead areas may be equally vulnerable. For this reason, the upper area of the cabin should be protected to an appropriate level. Relocation of emergency equipment from upper areas may be appropriate, and regulatory attention should consider to the differing fire hazards of upper and lower cabin areas.

3. Tactile Placarding (signs read by feel or touch)

Armrests and overhead compartments at rows associated with emergency exits should have a tactile system of identifying markings to facilitate location by crew and passengers whose vision has been debilitated by smoke and combustion. Such markings would be of critical importance to blind passengers.

C. Crewmembers

The effective intervention of crewmembers during a postcrash fire or any other emergency is necessary for the ultimate survival of the aircraft occupants. For this reason, certain protective measures should be taken on behalf of the highly trained crew to ensure their ability to provide leadership during the emergency.

1. Training

The subsequent discussion, also beyond the scope of the SAFER Committee is offered for consideration outside the SAFER Committee. All crewmember training should incorporate material derived from the latest industry and FAA testing which demonstrates the hazards of aircraft fires and suggests actions and procedures appropriate for the fire situation. Education regarding stratification of heat and gases, fire patterns, fiber fabric flammability, necessity for crawling or stooping during cabin egress, and the effects of smoke and gases on mental acuity and judgment should be incorporated in required crew training.

3. Protective Equipment

Any special protective equipment provided for crewmembers must be located at their stations and be immediately accessible. Crew ability to aid passengers in evacuating an aircraft during a fire may be enhanced by protective breathing devices and gloves; however, tests should be conducted which address the specific problems of time required to don the equipment, ability to direct passengers and be understood, and freedom of movement.

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ASSESSMENT OF ADEQUACY OF CURRENT STANDARDS AND EXISTING TECHNICAL BASIS FOR NEAR TERM UPGRADING OF RULES

Interior Materials:

An assessment of the adequacy of current standards begins with the issuance of NPRM 69-33 on August 12, 1969. This notice considered amending many sections covering emergency evacuation and operating procedures in addition to materials fire safety. It was the result of much study and testing by the FAA, materials producers, suppliers and the airframe industry. The pertinent sections of 69-33 dealt with compartment interiors, cargo and baggage compartments and electrical system fire and smoke protection. Those sections, with relatively minor changes are current in todays FAR Part 25 Amendment 25-32.

The 69-33 rules were prepared to be used in procurement specifications as acceptance criteria for materials as well as minimum standards for assemblies as installed in aircraft. ASTM tests, nonstandard tests and other special tests were devised such as for ceiling panels in an effort to simulate real fire situations. In addition to test method development, all candidate aircraft materials that could be made available from a country-wide search were tested to determine the then current state-of-the-art flammability level. With this background some tests were found more suitable for specific shapes or generic classes. All had various degrees of severity but were not correlatable with each other and none could measure how a material would burn in actual fire scenarios. With no technology available to relate lab tests to actual fires the Bunsen burner test was selected as the most suitable materials test for industry needs. A significant improvement was made, however, from a horizontal burn rate requirement in prior rules to a self-extinguishing requirement for large area materials in a vertical position. This Bunsen burner test, was and still is, a very good measure of the materials flammability, as well as a good rating method for self-extinguishing material. Material improvements have been made to reduce flammability. This was usually done by adding self-extinguishing agents to existing materials which may increase both smoke and toxic decomposition products. In an effort to continue improvement in aircraft fire safety the FAA requested comments on two new proposed rules, one for smoke and another to measure toxicity. It was then recognized that fire, smoke and toxicity could not be considered individually, but must be combined so the proposed rules were properly withdrawn. The wide-body jets were then just being designed and FAA required that smoke data be submitted on interior materials to assure that smoke was considered in the normal material selection compromise.

During this 10 year time period efforts were not lacking to increase safety by improving materials, laboratory and full size fire test methods and analytical modeling of fire. In retrospect, one of the largest programs relating to a single subject (i.e., fire safety) was undertaken in this country by involving representative groups from all organizations involved in

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fires. Specifically related to aircraft was the NASA FIREMAN program, the many FAA programs including construction of the new burn test facility at NAFEC, the many programs by trade organizations representing the material producers and their in-house and supplier work, the new courses and programs at universities as well as the aircraft industry itself. Concern was expressed by many persons and organizations that a test for a "self-extinguishing" or "fireproof" material by its title was misleading in the way it might react in an actual fire. In addition, a method urgently needs to be developed to measure how "good" a material really needs to be since it was recognized that material improvement beyond some point would do little to improve personnel survival but would be very costly.

Design Goals and Mandated Standards:

Industry design goals are to meet or exceed every FAR mandated requirement. Improvements in safety are a never-ending design goal of government and industry. This is evidenced by periodic upgrading of FAR standards and incorporation of advances in aircraft design by industry. When considering advanced technology, Federal Air Regulations normally lag behind industry because of finite times required to revise existing regulations. Industry often incorporates newly developed technology during these periods. It would be difficult for government to eliminate this time lag since most new technology is the result of industry research and development programs. If new technology is produced by government, it is then necessary for industry to evaluate its full impact prior to FAR incorporation.

When considering state-of-the-art improvements, federal regulations can, and often do, lead industry. This normally occurs when government decides to upgrade standards by incorporation of proven existing hardware or technology. Sometimes, this is a result of current aircraft accident investigations which may reveal facts not previously known or understood. In addition a review of accident data has shown that the major survival fire threat is not the in-flight fire but rather the survivable impact post-crash fire. Comments relative to the aircraft fuel's part in this accident scenario are contained in later paragraphs.

Existing technology consists of many tests for flammability, smoke and toxicity. It is recognized that these three types of hazards cannot be rated individually to determine whether a material has been "improved". For this reason a number of tests have been attempted in a series of "screens" to rank a material in the same sequence as a selected fire scenario in a fuselage test section. After considerable effort, this has been found largely unsuccessful because a material in the usual standard laboratory test does not "see" the same heat flux and oxygen flow present in a large fire. Toxicity and flash fire have not been included in this approach either and particularly toxicity has been considered necessary for rule making. Technology is only now being developed which can analytically relate laboratory data to cabin environments and eventually some form of this approach may be the basis of a new rule.

Existing test facilities range from those required for materials qualification to those useful in design evaluation and fire research. Most

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concerns in the airplane material business have a capability to perform the standard Bunsen burner test for material qualification, some are able to perform the smoke test using the NBS chamber and a range of capability in toxic gas analysis. Most airframe manufacturers have additional test and analysis capabilities including the Ohio State University Release Rate Calorimeter and various scales of Fire Simulation Facilities. A large Cabin Fire Simulator is available at McDonnell Douglas and a full scale C-133 fuselage simulator is at NAFEC. Other specialized aerospace facilities are located at NASA Ames, Johnson Space Center and Boeing. Standard tests have been established for flammability and smoke and are accepted by the testing community. No standards have yet been established for the Ohio State Calorimeter nor products of combustion.

A major technical deficiency at the present time is the lack of a good modeling technique. Fire modeling for aircraft is different from general fire modeling such as for buildings. Building fire models includes more detailed physics principles than is needed for aircraft and these should be properly eliminated. Two fire models are needed for aircraft and both terminate at flashover rather than full destructive involvement of a structure. The first, for material rating, must predict the cabin environment from laboratory data. The second predicts flame propagation in a cabin and can be used in design and for evaluating safety.

A second major deficiency is our lack of understanding of toxicity. Technology is lacking in the definition of the maximum time an occupant can breathe a given gas concentration in a cabin environment. This is further complicated by combining gases at elevated temperature. Psychological factors involve a level of understanding technology which is apparently beyond our current capability. This understanding is needed for ultimate accuracy which may never be achieved, but a total understanding not needed for rulemaking. In the case of toxicity, panic or fear would increase breathing rate and therefore decrease escape time.

It is believed that after approximately 10 years of attempting to develop coherent and useful rules, programs are now underway that will develop the technology, facilities, test methods and costs from which one or more of several approaches for rules may be selected and direct future research needs.

Existing rules which employ the current FAR Part 25.853, 25.855, and 25.1359 bunsen burner flammability tests, coupled with nonregulatory smoke testing and a knowledge of thermal decomposition products, provides the designer with reasonable input for the usual compromises in selection of materials. Full-size component tests in simulated fire tests prove the suitability of new aircraft designs. As there is no data or technique available to correlate th increase in cabin survivability with each improvement, experience is used to decide on the importance of employing newer materials and designs. Recent accident statistics indicate this procedure is reasonable even though it may not be the theoretical optimum.

The Committee has identified an area where an improved test method should be quickly incorporated. The vertical Bunsen burner test (FAR Part 25, Annex F)

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should be modified to provide a better test for materials which drip and burn away from the burner flame. This change may evolve into a separate approach for materials required to be tested, e.g., 1" thick (foam) and others, but is within the state-of-the-art and could be the subject of a near-term regulation change. ASTM Subcommittee F-7 is already charged with responsibility to recommend a revised test for regulatory purposes.

Laboratory tests indicate that the radiant heat resistance of emergency escape slide material can be substantially improved. Materials have been developed which reflect radiant heat and extend the useful exposure life of the slide, and are now being evaluated by the FAA.

For the long term, as discussed above, the OSU calorimeter device modified for smoke and toxic gas measurement, probably coupled with an analytical model to relate OSU test data to cabin environment, show promise for providing the basis for regulatory action. Standardizing tests to run in the unit and agreeing on personnel hazard limits is yet required to achieve a meaningful measure/correlation of human survivability in a postcrash fire situation.

Full-scale cabin-fire testing in facilities such as the FAA and other government industry facilities provides for baseline data for cabin fires. It is not intended that regulations would be written around these tests; rather, the data provides guidance for more detailed design improvements. It is expected that full-size component testing (e.g., waste containers) in realistic fires will continue to provide rationale for improving both materials and designs, regardless of future rules for materials.

RECOMMENDED GOALS FOR FAA RULEMAKING

Cabin Materials and Evacuation Slides

The Committee perceives that the existing FAR 25 Bunsen burner test is adequate for separating burning from self-extinguishing materials and for measuring the flammability of self-extinguishing materials except those which drip and melt away from the flame. For the materials that drip and melt away like polyurethane foam, a revised FAR test method should be developed.

Development of a radiant panel test method and an improvement in the heat resistance of evacuation slides will be completed in the near future. These improvements should be evaluated and implemented as soon as they are available.

Fuel System

The SAFER Committee believes that technology exists to support rulemaking to minimize the hazard of fuel tank explosions during post-crash fires. It is considered that fuel tank vent flame arrestors or explosion suppression systems used in some commercial production aircraft to protect against lightning-induced ignition at fuel vent outlets might also be able to delay propagation of ground fires through the vent system and the subsequent explosions in intact fuel systems to provide additional time for safe evacuation.

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A flame arrestor consists of a web of quenching channels. When a flame front enters a relatively cold quenching channel, heat from the flame flows into the channel wall at a rate exceeding the rate of heat generation so that the temperature decreases and the combustion reaction ceases. If the total heat capacity of the arrestor is small, then the temperature of the arrestor will increase rapidly to a value where the arrestor fails. A flame stabilized on the flame arrestor surface could heat a normally quenching channel to a temperature where the flame can penetrate unless the cooling effect of the unburned gases approaching the flame arrestor maintain the quenching surfaces below the fuel ignition temperature. However, it is believed possible to design an arrestor to prevent flame penetration and propagation through the vent system for a period of time equal to the time required for an external fire to penetrate the undersurface of an empty wing tank. Testing of flame arrestors in a simulated crash fire environment has not yet been conducted and would be necessary to obtain basic data on their effectiveness in this environment.

An explosion suppression system includes a flame radiation sensor in the vent outlet tube to detect the presence of an oncoming flame front and a fire extinguishant discharge system in a fuel tank for automatic early and rapid suppression of the combustion process when it reaches the tank. This system can provide fuel tank vent explosion protection similar to a properly designed flame arrestor if provision is made for adequate extinguishant dispersion. This requires continued availability of electrical power to enable sensing of any internal combustion process induced by external fire effects and triggering of timely extinguishant dispersal. In addition the system must be capable of effective operation at elevated temperatures due to external heating effects. Data on explosion suppression system tests in a simulated crash fire environment are needed to substantiate their effectiveness in this environment.

The SAFER Committee also believes that technology exists to minimize the post-crash fire hazard by providing means to shut off engine fuel supplies to further reduce fuel fire possibilities.

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